Behaviour of RC Beams Strengthened by CFRP under Fatigue Load

by

Chin Siew Choo

Dissertation submitted in partial fulfillment of
the requirements for the
Bachelor of Engineering (Hons)
(Civil Engineering)

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CERTIFICATION OF APPROVAL

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A project dissertation submitted to the
Civil Engineering Programme
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Approved by,

(Assoc. Prof. Dr. Nasir Shafiq)

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TRONOH, PERAK
June 2006

CERTIFICATION OF ORIGINALITY

This to certify that I am responsible for the work submitted in this project, that the original work is my own except as specified in the references and acknowledgements, and that the original work contained herein have not been undertaken or done by unspecified sources or persons.

(CHIN SIEW CHOO)

ABSTRACT

One of the major tasks for the construction industries worldwide is rehabilitation of structurally deteriorated or functionally obsolete reinforced concrete structures. The major portion of the infrastructure is built from reinforced concrete and corrosion of reinforcing steel was found to be one of the principal cause of deterioration. The solution to this task has been proved by the use of externally bonded carbon fibre reinforced polymer (CFRP) strips to strengthen reinforced concrete structures. In this study, the behaviour of reinforced concrete beams strengthened with externally bonded carbon fiber reinforced plastic (CFRP) under fatigue load were investigated. The capacity of CFRP strengthened beams subjected to fatigue loads, fatigue characteristics of reinforced concrete beam strengthened by CFRP, fatigue life and behaviour of the reinforced concrete beam were studied. Data obtained from experimental investigations were statistically analyzed and valid correlations were obtained.

ACKNOWLEDGEMENT

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TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

CHAPTER 1

INTRODUCTION

1.1 Background of Study

One of the major tasks for the construction industries worldwide is rehabilitation of structurally deteriorated or functionally obsolete reinforced concrete structures. The solution to this tough task has been proved by the use of externally bonded carbon fibre reinforced polymer (CFRP) strips to strengthen reinforced concrete structures. Carbon fibre reinforced polymer (CFRP) materials is being increasingly used in civil engineering structures as strips or laminates, as fabric wraps and as cables in the form of parallel wire bundles. Research so far has mostly concentrated in its use in repair and in strengthening of existing structures. The range of applications cover concrete elements, masonry structures and the possibility also exists for strengthening timber elements. The method of strengthening is typically by adhering the CFRP strips or laminates by means of specially formulated adhesives to the external surface of the structure. When set, the CFRP laminates act compositely with the parent material resisting any applied load in a composite manner

Historically, concrete members have been repaired by post tensioning or jacketing with new concrete in conjunction with a surface adhesive. Since mid-1960s, epoxy bonded steel plates have been used to retrofit the flexural members. However, steel plates have a durability problem due to this application whereby corrosion may occur along the adhesive interface. In the 1980s, a new technique was developed involving the replacement of steel plates by fibre reinforced polymers (FRP), or simply composites wrapped or epoxy-bonded to the web or tension side of concrete, in the forms of thin laminates or fabric. FRP materials have been used successfully in the aerospace and automotive industries for three decades.

The FRP offers the engineers an outstanding combination of properties, such as low weight; much easier to be handle on site, immunity to corrosion, excellent mechanical strength and stiffness, and the ability of formation in the very long length have eliminate the need for lapping at joints. Although CFRP is a relatively expensive material as compared to steel, the total rehabilitation project costs could be about 20% lower by using CFRP than steel due to the savings in construction expenses. Furthermore, since the cost of the material is very high, but with its potential for widespread application, the process of manufacture could be improved and cost could be brought down to acceptable levels. It is well known that the reinforced concrete beams strengthened with externally bonded FRP or CFRP to the tension face can exhibit ultimate flexural strength greater than their original flexural strength. However, these FRP and CFRP strengthened beams could lose some of their ductility due to brittleness of FRP and CFRP plates.

Carbon fibres are the predominant reinforcement used to achieve high stiffness and high strength. The term carbon fibre (graphite fibres in the USA) covers a whole family of materials which encompass a large range of strengths and stiffness. The density of carbon fibre is of the order of 1900kg/m^3. Typical fibre moduli may be 230-300 GPa, whilst strengths after processing are in the range of 3000-5000 MPa.

Carbon fibre is most commonly produced from a precursor of polyacrylonitrile (PAN) fibre which is processed by first stretching it to achieve a high degree of molecular orientation. It is then stabilized in an oxidizing atmosphere while held under tension. The fibres are then subjected to a carbonizing regime at a temperature in the range 1000-3500°C. The degree of carbonization determines such properties as elastic modulus, density and electrical conductivity. As an alternative to the use of PAN, routes via the use of pitch and rayon have been successfully utilized and such fibres are commercially available. These fibres tend to be of lower performance than PAN-based fibres. They are also cheaper due to their use of a lower cost precursor.

1.2 Problem Statement

Rehabilitation of structurally deteriorated or functionally obsolete R.C structures is a major problem in the construction industry worldwide. A growing number of reinforced concrete structures are reaching a stage where deterioration is affecting its serviceability, load carrying capacity and safety. Together with the introduction of fibre reinforced polymers (FRP) for strengthening and rehabilitation, this has exposed the need for reliable methods for estimating stiffness and strength of deteriorating and retrofitted concrete structures. By using carbon fibre reinforced polymer (CFRP) laminates has proved to be an effective means of upgrading and strengthening reinforced concrete (R.C) beams.

1.3 Objectives and Scope of Study

The main objectives and scope of this study are defined as below:

1. To determine the capacity of CFRP strengthened beams subjected to fatigue loads
2. To determine the fatigue characteristics of reinforced concrete beams strengthened by CFRP
3. To determine the fatigue life of the reinforced concrete beams under CFRP
4. To determine the behaviour of R.C beams strengthened by CFRP plates
5. To analyze the experimental results

CHAPTER 2

LITERATURE REVIEW/THEORY

2.1 Carbon Fibre Reinforced Polymer (CFRP)

Fiber Reinforced Polymer (FRP) has been used successfully for decades in aerospace, shipbuilding and sporting goods industries. They are constructed of fibers (such as glass, carbon and Kevlar) embedded in a resin matrix. The function of the resin is to protect the fibers and to distribute the loads evenly among them. Various coatings can be added to the fibers for better bond to resin matrix. A major advantage of FRPs compared to other structural materials is their anisotropy whereby FRPs have physical properties that are different when measured along different axes or directions. By orienting the fibers in the desired direction, one can achieve the required strength in each direction. [1]

Strengthening measures are required in structures when they are required to accommodate increased loads. Also, when there are changes in the use of structures, individual supports and walls may need to be removed. This leads to a redistribution of forces and the need for local reinforcement. In addition, structural strengthening may become necessary owing to wear and deterioration arising from normal usage or environmental factors. Concrete structures need to be strengthened for any of the following reasons; load increases due to higher live loads; increased wheel loads, installations of heavy machinery, or vibrations; damage to structural parts due to aging of construction materials or fire damage; corrosion of the steel reinforcement, and/or impact of vehicles; improvements in suitability for use due to limitation of deflections; reduction of stress in steel reinforcement and/or reduction of crack widths; modification of structural system due to the elimination of walls/columns and/or openings cut through slabs and errors in planning or construction due to insufficient design dimensions and/or insufficient reinforcing steel. [2]

CFRP laminates reinforcing technology provides a solution for strengthening problems of concrete structures. It provides great strength, high modulus of elasticity, and outstanding fatigue resistance. It is a very lightweight non-corrosive material, that requires minimal preparation of laminates, and it's alkali resistant. It is an economic method that requires very short contract times. Based on the worldwide research and development work, the use of CFRP laminates to rehabilitate structures is already a routine for many firms in Western Europe and Japan. In the U.S., Sika has introduced Sika CarboDur, which is a CFRP laminates used to strengthen concrete, steel, or wooden structures. CFRP materials will not replace traditional construction materials, but will be used increasingly to supplement them as needed. [2]

Researcher Dr. Abdul-Hamid Zureick Prof; has performed an integrated field/laboratory approach to rehabilitate the Lee Road Bridge over Interstate 20 in Douglas County, GA, using CFRP [17]. This project is funded by the Georgia Department of Transportation (GDOT) in cooperation with the Federal Highway Administration (FHWA). The project took workers less than a day to complete what could have taken several weeks to do traditionally and, so far, laboratory tests have determined that CFRP can make bridges 30 to 40 percent stronger than the original design. [3]

Carbon fibres are the stiffest and strongest reinforcing fibres for polymer composites, the most used after glass fibres. It is a made of pure carbon in form of graphite which have low density and a negative coefficient of longitudinal expansion. Carbon fibres are very expensive and can give galvanic corrosion in contact with metals. They are generally used together with epoxy, where high strength and stiffness and stiffness are required. In addition, carbon fibres are produced by the PAN or the pitch methods, which are called precursors. The PAN method separates a chain of carbon atoms from polyacrylnitrile (PAN) through heating and oxidation whereas pitch method pulls out graphite threads through a nozzle from hot fluid pitch. [4]

In general, carbon fibres are produced from PAN precursor fibres by three processing stages: (1) stabilization, (2) carbonization, (3) graphitization (Refer to figure 2-1). In the stabilization stages, the PAN fibres are first stretched to align the fibrillar networks within each fibre parallel to the fibre axis, and then they are oxidized in air at about 200 to 220°C while held in tension. [4]

The second stage in the production of high strength carbon fibres is carbonization. In this process, the stabilized PAN based fibres are pyrolyzed (heated) until they become transformed into carbon fibres by the elimination of O, H and N from the precursor fibre. The carbonization heat treatment is usually carried out in an inert atmosphere in the 1000 to 1500°C range. During the carbonization process, turbostratic graphite like fibrils or ribbons is formed within each fibre which greatly increases the tensile strength of the material. [4]

At third stage, or known as graphitization treatment, is used if an increase in the modulus of elasticity is desired at the expense of high tensile strength. During graphitization, which is carried out above 1800°C, the preferred orientation of the graphite like crystallites within each fibre is increased. [4]

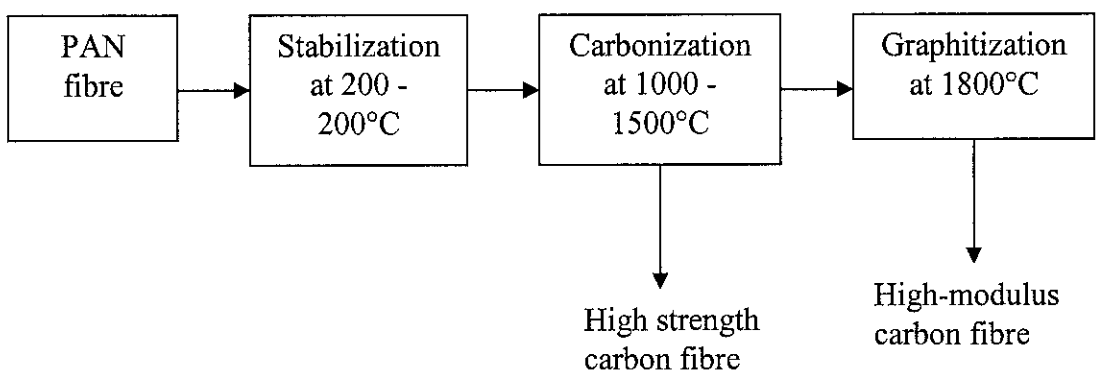

Figure 2-1: Production Stage of Carbon Fibre

The pultruded CFRP laminate reinforcing consists of bonding the CFRP strip with the concrete structure using a high- strength epoxy resin as the adhesive. The CFRP strips are manufactured using a pultrusion process. The pultrusion principle is comparable with a continuous press. Normally, 24,000 parallel filaments are pulled through the impregnated bath, formed into strips under heat, and hardened. These strips are uni-directional; the fibres are oriented only in the longitudinal direction. Correspondingly, the strip strength in this direction is proportional to the fibre strength and, thus very high. Strips are produced with strengths of approximately 3,000 MPa in the longitudinal direction, and with the thickness of up to 1.5 mm and widths of up to 150 mm. [2]

In order to achieve an optimum composite action, the preparation of the bonding surfaces of the strip and concrete is critical. The strips must have the outermost layer of their bonding face, normally matrix-rich, removed to expose the fibers. Just before the bonding, the bonding surface is carefully cleaned with acetone. The concrete surface is treated by sand blasting, high pressure water jets, stoking, or grinding. Shortly before the bonding, it is cleaned with a vacuum cleaner. Concrete must be at least 6 weeks old, and have a minimum tensile strength of 1.5 MPa. Highly filled epoxy resin adhesive is used for the bonding. [2]

Properties of the material are one of the important factors to determine the strength of the material. Thinner CFRP plate thickness might have higher strength than thicker CFRP plate thickness because of the properties of the material. The properties of the CFRP are shown in the Table 2-1.

Table 2-1: Properties of CFRP

Properties		Sika CarboDur XS	SIka CarboDur S
E-Modulus (mean value)	N/mm^2	165,000	165,000
E-Modulus (minimum value)	N/mm^2	> 160,000	> 160,000
Tensile strength (minimum value)	N/mm^2	> 2,200	>2,800
Tensile strength at break (mean value)	N/mm^2	2,400	3,100
Strain at break (minimum value)	%	>1.36	>1.70

The CFRP strips have a fibre volume fraction of about 65%, have a apparent density of 99.7 lb.ft3 (1.6 g/cm3), and are black in color. Theoretically, the stripes can be made in any dimensions. The CFRP stripes used in research are about two inches (50 mm) wide, one-twentieth inch (1.2 mm) thick. The temperature resistance of these CFRP strips is about 500°C. The shelf life of these strips is unlimited. CFRP strips are uni-directional and have a longitudinal tensile strength of 348 ksi (2,400N/mm2). The lateral strength of the strips is negligible. The strips are elastic until break. The modulus of elasticity is 22.5 x 106 psi(155,000 N/mm2). The elongation at break is 1.4%. [6]

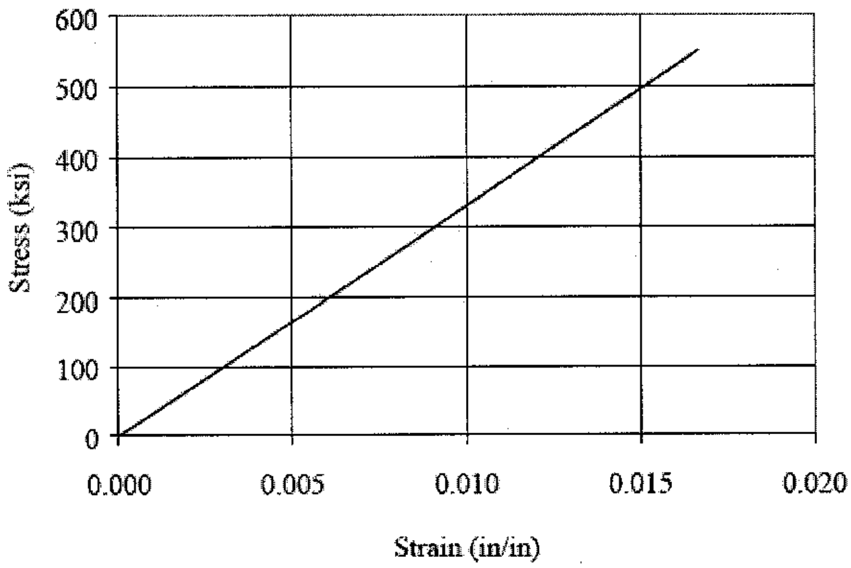

Figure 2-2: Stress-Strain Behaviour of CFRP

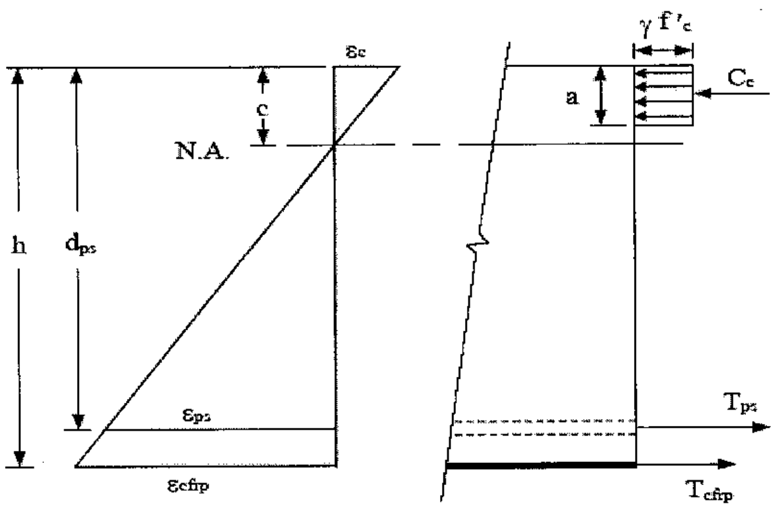

Figure 2-3: Stress, Strain and Force Diagram of CFRP

The advantages of the CFRP are very high strength, outstanding fatigue resistance, non-corrosion, excellent alkali resistance, low weight, low thickness, available in any length, and economic to apply. [21] It is well known that reinforced concrete beams strengthened with externally bonded FRP or CFRP to the tension face can exhibit ultimate flexural strength greater than their original flexural strength. However, these FRP and CFRP strengthened beams could lose some of their ductility due to brittleness of FRP of CFRP plates. [5]

2.2. Static Performance of Reinforced Concrete and CFRP

Shahawy and Beitelman (1999) looked at static performance of T-beams strengthened with CFRP. They statically tested ten T-beams, nineteen feet long, with differing wrap patterns varying from fully wrapped to partially wrapped stems. The partially wrapped stems only had CFRP on the bottom of the stem and not on the sides. The beams had from 0 to 4 layers of CFRP attached to them. Two-point loading was used for the tests. From their static tests, ultimate flexural strength was shown to increase from 19% to 70% with a rate of increase beginning to diminish past two layers. They determined that concrete crushing was occurring before the full strength of more CFRP layers could be realized. It was also concluded that perhaps partial wrapping was not the best way to wrap the beams. When a CFRP layer was only placed on the bottom of the stem, horizontal cracks developed along the level of the reinforcing steel causing delamination of the concrete. The fully wrapped beams were found to be more ductile than the partially wrapped beams, which seems odd and does not seem to follow what most other researchers are saying. [7]

Copozucca and Cerri (2002) looked at the behavior of RC beam models strengthened after cracking with CFRP. After running single point bending tests on different beams with one and two layers of CFRP, they concluded that models with more layers of CFRP will have more strength but less ductility then those with fewer or no layers of CFRP. This could lead to undesirable brittle failures. With only one layer of CFRP, a good level of ductility was shown from their Moment-Curvature plots. [7]

2.3. Fatigue Performance of Reinforced Concrete and CFRP

Shahawy and Beitelman (1999) also looked at fatigue performance of strengthened T-beams. Six beams, nineteen feet long, were cyclically loaded for up to 3,215,000 cycles. There was one control beam, two beams had 2 layers of CFRP with the stem fully wrapped and two beams had 3 layers of CFRP with the stem fully wrapped. A sixth beam was damaged in fatigue for 150,000 cycles before 2 layers of CFRP were added to its stem. The damaged beam that had been rehabilitated showed improved fatigue life similar to the undamaged beams that were wrapped before they were loaded. This led to the conclusion that severely cracked beams in the field could be successfully repaired with CFRP. From the tests it was also concluded that the stiffness of all of the wrapped beams was greater than the unwrapped control beam. Finally the testers concluded that full wrapping of beams with CFRP is an effective method of rehabilitating and strengthening fatigue critical structures. [7]

Barnes and Mays (1999) conducted some fatigue tests on reinforced concrete beams with CFRP plates attached. Five identical beams were tested in fatigue, two original and 3 strengthened beams. Three different aspects of loading were addressed. These aspects included the following: apply the same loads to plated and unplated beams, apply loads that would give the same stress range in the rebar to each, or apply the same percentage of ultimate load capacity to both beams. All three of these aspects were addressed in this single test. The final results of this experiment showed that a plated beam had significantly longer fatigue life than an unplated beam with the same loading. A plated beam also has a longer fatigue life than an unplated beam when the rebar is loaded to identical stress ranges. Finally it was noted that an unplated beam had a longer fatigue life than a plated beam when each was loaded to the same percentage of the predicted ultimate strength. [7]

2.3.1 Laboratory Testing Program on Fatigue Conditions

The beam tested was subjected to cyclic loading to simulate actual highway loading. The setup for the fatigue portion of the test is shown in Figure 2.2. The lab setup required to accommodate the beam consisted of a large preexisting steel frame anchored to the lab floor. The frame consisted of two W-shaped steel beams about 25 feet long that ran parallel to each other seven feet apart. Other W-shaped beams provided bracing. The lab was not big enough to allow the P/C beam to be placed parallel or perpendicular to the frame. The only way the beam would fit was to skew it diagonally to the frame. This allowed for just enough room to walk around one end of the beam in order to maintain the functional capacity of the lab, although one end of the beam was supported on the tie down floor and the other on the on grade slab. [7]

Since the P/C beam had to be skewed, the actuators had to be skewed as well. Two hydraulic actuators were used to load the P/C beam. The actuators each had a 55 kip capacity and were attached to the frame using several large C-clamps. They were also braced in several directions, and welded to the frame to prevent them from moving from side to side. Small movements of the actuators did not appear to have a significant effect on the fatigue loading. [7]

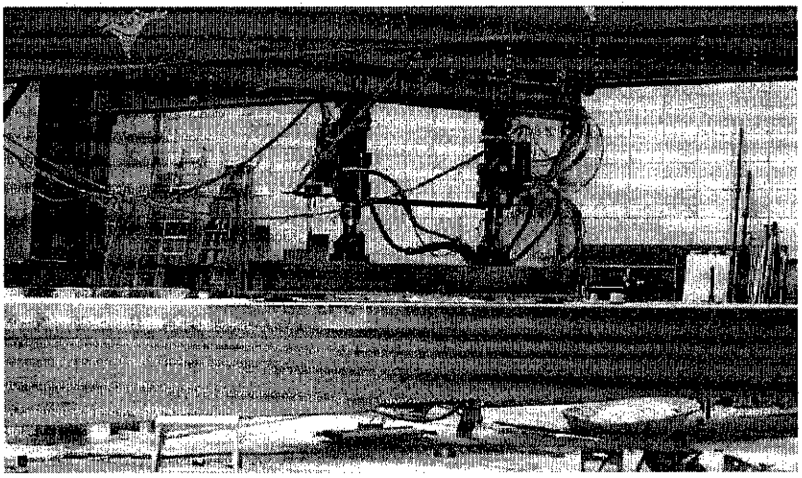

Figure 2-4: Fatigue Loading Setup

A cross-sectional view of the fatigue test is provided in Figure 2.3. A 10 ft steelspreader beam was used because the actuators were only 4 feet apart. It was not attached to the actuators to prevent any potential binding. The spreader beam was supported by the pin and roller on top of the beam. The weight of the actuators kept the spreader from moving. During the fatigue testing, a minimum load of 2 kips was applied at all times to prevent any bouncing or movement of the spreader beam. [7]

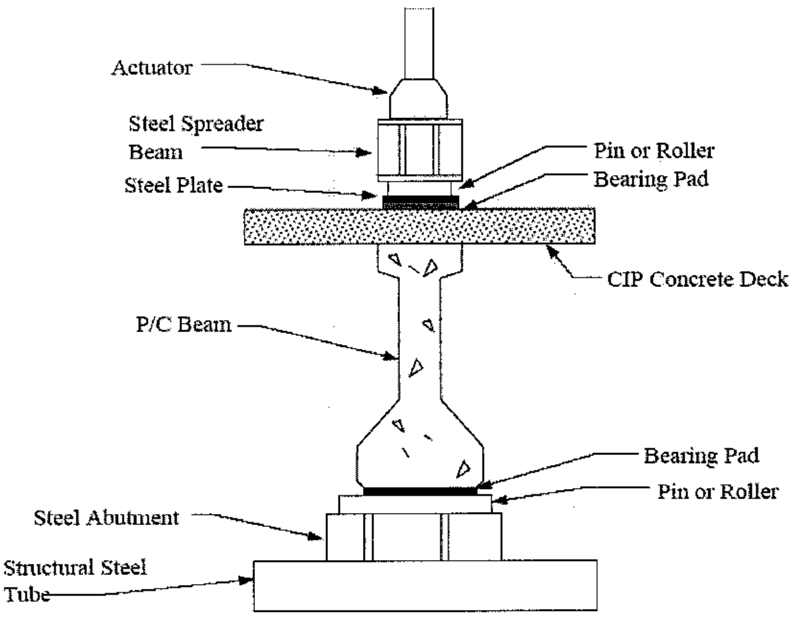

Figure 2-5:Cross-section of Fatigue Loading Setup

2.4. Application of CFRP Bridge Repairs

Shawhawy and Beitelman (1996) used CFRP to restore strength to impact damaged P/C girders (I-shaped) in Florida. The exterior and first interior girders both experienced significant section loss in the bottom flange and severe cracking in the web. Load tests conducted after the impact indicated that the strength of the two damaged girders had been reduced by approximately 20%. A repair strategy using CFRP was developed primarily because of the high replacement cost. The estimated cost to replace the two damaged girders was $300,000. [7]

Each damaged girder was strengthened with 2-layers of CFRP sheets in longitudinal direction to increase the flexural strength. Full depth transverse CFRP sheets were also used to increase the shear strength and seal the cracks. The cracks on the sides of the beams were not injected with epoxy before the installation of the CFRP sheets. The CFRP material was protected with a layer of UV resistant primer and a layer of fire resistant material. Also, the exterior lane of the strengthened bridge was closed to traffic for 24 hours to allow the CFRP to cure. Load tests conducted after the bridge had been strengthened indicated that the original service condition of the girders was restored. [7]

2.5. Bridge Deck Strengthening

The field portion of the program involved three bridges around the state of Iowa that had been damaged by overheight vehicles. The bridges were near Altoona, Osceola, and De Soto, Iowa. Each bridge was repaired using CFRP. For example, the Altoona Bridge was damaged was on the south bound portion of the IA Highway 65 bridge that crosses IA Highway 6 in the vicinity of Altoona, Iowa. This four span bridge consists of two 96.5 ft main spans and two approach spans – the north one 36 ft long and the south one 46 ft long. A cross-section of this bridge is presented in Fig. 1. All six of the LXD P/C girders in one of the main spans were damaged by an overheight vehicle traveling east on IA Highway 6. Although, as illustrated in Fig. 2, all 6 girders were damaged approximately 30 ft from the center pier, most of the damage was to the first two girders. Damage to Beam 1 consisted of spalling of concrete from the bottom flange and the severing of one strand. Damage to Beam 2 (shown in Fig. 3) was the most severe in that significantly more concrete spalled from the bottom flange exposing five strands two of which were severed. [7]

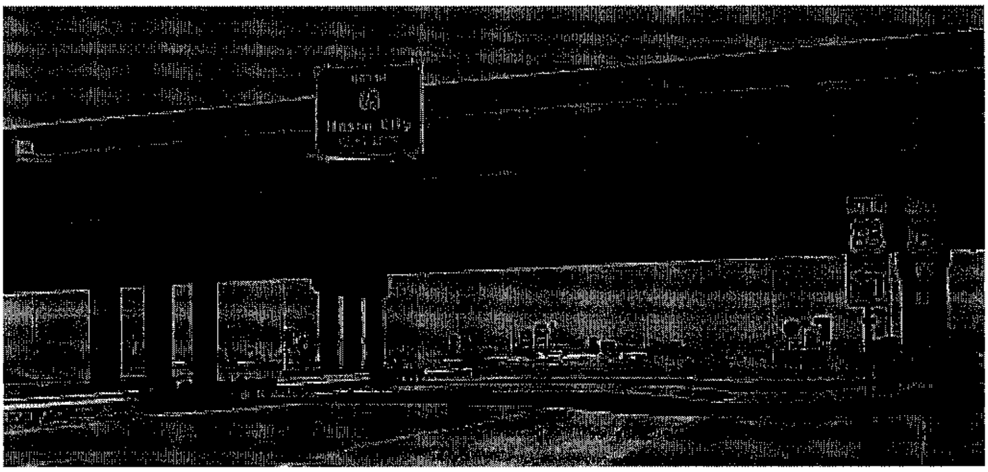

Figure 2-6: Overall View of Altoona Bridge

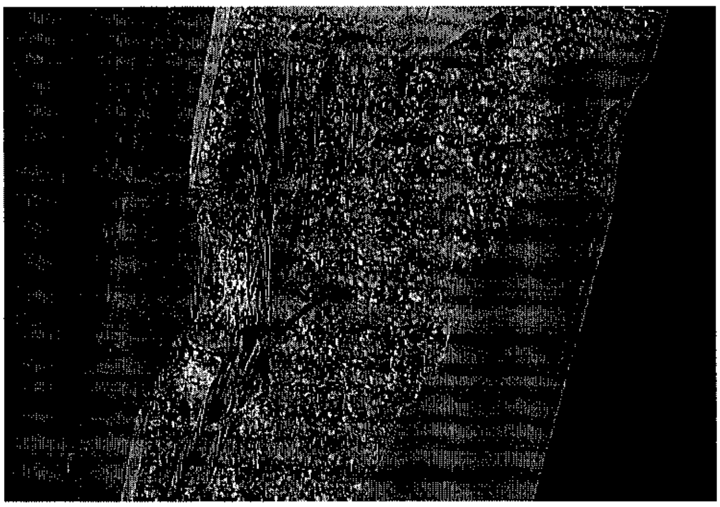

Figure 2-7: Photograph of the Damaged Beam 2 in the Altoona Bridge

2.5.1. Field Testing

As previously stated, this bridge was tested before and after the CFRP was installed so that the effectiveness of the strengthening system could be determined. Instrumentation consisted of strain gages and deflection transducers. A total of 24 gages were used on the bridge. Deflections were measured at the centerline of all six beams in Span 2. Two Iowa DOT trucks (rear tandem) were used in the testing of the bridge. The two trucks (rear tandem) used in the testing prior to the repairs had an average weight of 51,100 lbs, while the average weight of the two trucks used in the final tests after repairs was 46,700 lbs. Static as well as dynamic load tests were performed on the bridge. Thirty-two different load tests, with the trucks positioned to produce the largest positive and negative moments in the various girders were completed in the static portion of the test. Dynamic data were obtained with one of the trucks traveling at three different speeds: 3-8 mph, 30-35 mph and 65-70 mph. [8]

2.5.2. Field Repairs

Prior to installation of the CFRP, the manufacturer's recommended patching material and procedures were used to repair the spalled concrete on the various beams, CFRP plates were attached to the most heavily damaged beam – Beam 2 after the patch material had cured. Four 4-in. wide by 75 ft long protruded CFRP laminates (shown in Fig. 2-6) were installed on the bottom flange of Beam 2 using an epoxy-resin which was applied to both the laminate and the P/C girder. A rubber roller was used to enhance the bond. The tensile design strength of the CFRP laminates was 406 ksi. After installation of the four laminates, a CFRP wrap was installed in the vicinity of the patch (80 in. of the girder was wrapped) to confine the patch and to prevent any plate debonding. Five CFRP strips (approximately 6 ft long which was sufficient length to cover the bottom flange and all but approximately the top 1 in. of the web) were installed. Similar CFRP sheets were installed at the location of the patches in the other beams to assist in confining the patches. [8]

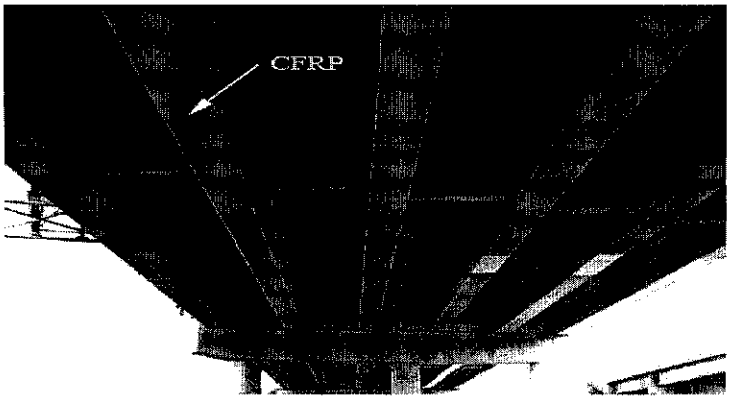

Figure 2-8: Photograph of CFRP on Beam 2 Altoona Bridge

2.6 Fatigue of Concrete

Static fatigue occurs when the stress exceeds about 70 to 80 percent of the short term strength for normal concrete and the analysis would determine whether R.C beams with CFRP would portray the same. Static fatigue characteristics are normally presented in 2 types of graph namely stress/strength against strain graph and stress against strain graph. Important parameter like the static fatigue failure envelope can be then obtained from the stress/strength ration against strain curve while for the stress against strain curve, hysterisis can be observed as per number of cyclic loads imposed. [9]

The other approach in fatigue analysis is base on constant range of alternating stress and is commonly known as S-N approach. S refers to the ratio of the maximum stress to the short term static strength and N is the number of cycles at failure. From S-N graph, endurance limit of R.C beams with CFRP can be determined as well as the fatigue limit of the R.C beams with CFRP can be estimated. [9]

CHAPTER 3

METHODOLOGY/PROJECT WORK

3.1 Procedure Identification

The methodology and the procedure of the project were divided into several topics which include:

3.1.1 Literature Review and Information Gathering

Information of CFRP was investigated and data was gathered by referring to respective books, journals and thesis developed by external and internal parties. All the information obtained was skimmed and chosen based on importance and relevancy. The information selected was done based on the several steps listed.

3.1.1.1 Preliminary literature research
3.1.1.2. Supplementary literature research
3.1.1.3 Analysis of relevant data
3.1.1.4 Preliminary data collection
3.1.1.5 Supplementary data collection

The best data and information relevant to CFRP was selected throughout the information gathering process and procedures of the literature review. The information obtained was studied, analyzed and understood thoroughly in order to have a better understanding of CFRP. For this research study, fatigue loading was taken into account to determine the strength of the reinforced concrete beam with CFRP strips. The reinforced concrete beam was tested with frequency of 5 Hz.

3.1.2 Hardware

3.1.2.1 Sika Carbodur – Heavy Duty CFRP Strengthening System

Sika CarboDur® is a heavy duty strengthening system for reinforced concrete and timber. It consists of two components which include Sikadur -30 adhesive for bonding reinforcement and Sika Carbodur laminates. Sika Carbodur is an external strengthening system that can be used on structural elements comprised of concrete, wood, or steel. The system consists of a pultruded, pre-cured carbon fiber reinforced polymer (CFRP) strip and a high modulus/high strength epoxy gel (Sikadur 30). The strip is 47 mils thick (1.2mm) and is available in 2, 3, and 4 inch (50, 80 and 100mm) widths. The tensile strength of the strip is 350 ksi with an elastic modulus of 22.5 x 106 psi. The strips are adhered using Sikadur 30 to structural elements to increase flexural capacity, fatigue resistance and reduce deflection.

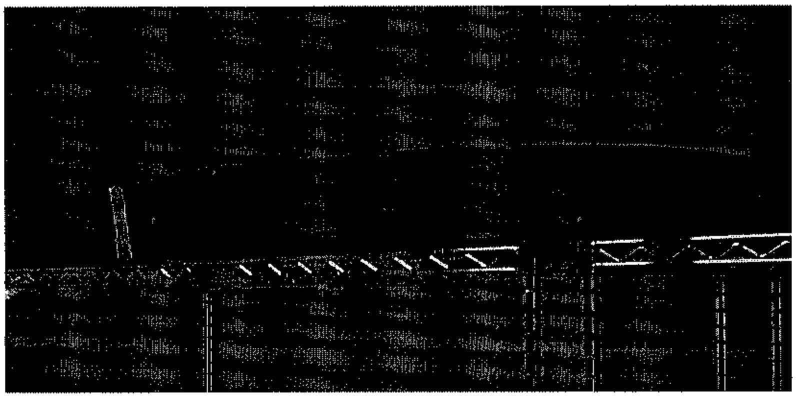

Figure 3-1: Carbon Fibre Reinforced Polymer

The Sika CarboDur System can be used to strengthen reinforced concrete and timber structures due to:

- Loading increases.
- Damage to structural parts.
- Serviceability improvements.
- Change in structural system.
- Design or construction defects.

The system has economic and performance characteristics which can benefit the contractor, engineer and owner. The contractor can reduce installation and surface preparation times because of the product's light weight and ease of installation. Because the material is non-corrosive and has an excellent strength to weight ratio, the engineer is provided with a fatigue resistant and strong product in a system that has minimal effect on dead weight or head room.

3.1.2.2 Sikadur -30 Epoxy Adhesive

Two component epoxy resin systems are particularly well suitable for the bonding of CarboDur plates to concrete, steel wood or bricks. This type of adhesive has very high mechanical strengths as well as a good chemical resistance against aggressive media. Good wetting properties on concrete, wood, etc., assure good bond characteristics. The function of the adhesive layers is above all to transfer the forces acting onto the joined elements.

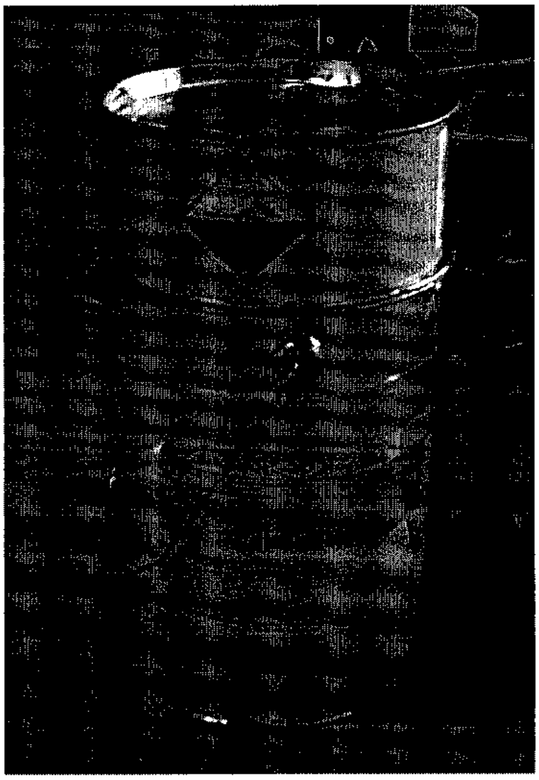

Figure 3-2: Sikadur-30 Adhesives

Sikadur-30 (refer to Figure 3-2) is supplied in factory proportioned units comprising the correct quantities of Part A (Resin) and Part B (Hardener). Both components are stirred thoroughly separately by hand-mixing using a spatula. The mixture prepared is 3:1 parts by weight whereby three from Part A (white paste) and one from Part B (black paste). All Part B is poured into Part A and mix thoroughly together until a uniform colour is achieved (typically 3 mins). A streaky colouration is indicative of inadequate or incomplete mixing. The mixture can then be applied onto the clean bottom surface of the beam once the mixture is mixed thoroughly into a creamy paste which is grey in colour.

Table 3-1: Properties of Sikadur-30 Epoxy Adhesives

Properties	Description
Static E-Modulus	12,800 N/mm^2
Adhesive Strength – Wet	Concrete failure (-4 N/mm^2)
Shear Strength	Concrete failure (-15 N/mm^2)
Thermal Coefficient Of Expansion (To Sika)	9 x 10^{-5} per °C (-10 to + 40°C)

3.1.3 Experimental, laboratory work and testing

The laboratory work covered the process of determining the behavior of the reinforced concrete beams that were strengthened by CFRP externally under fatigue loads. The work including producing six reinforced concrete beams and twenty seven cubes which was divided into two semesters. For the first semester, the consideration was given to the first four beams which had the same geometrical dimension which proposed to be 150 mm x 150 mm x 750 mm. In order to determine the compressive strength of the beams, nine cubes were cast from the same materials of the every two beams. The reinforcement bar used for all the beams were the same.

The reinforcement details of the beams were shown in the Figure 3-3:

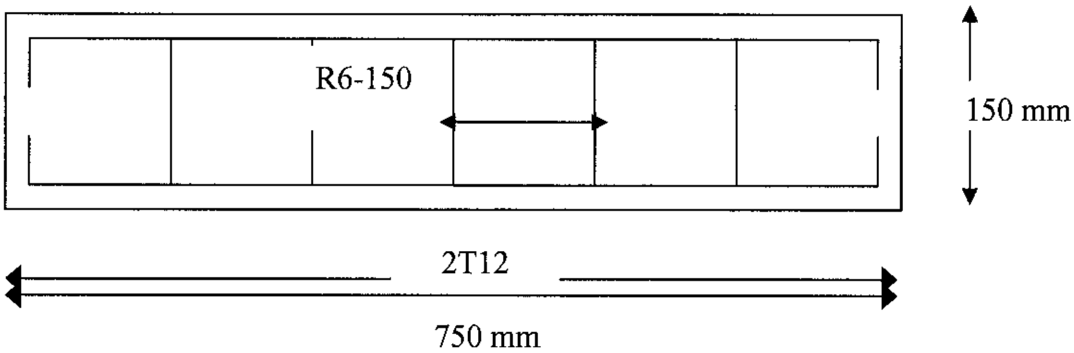

Figure 3-3: Beam Reinforcement Details

The first two beams were the control beams which without the application of CFRP (Refer to Figure 3-4).

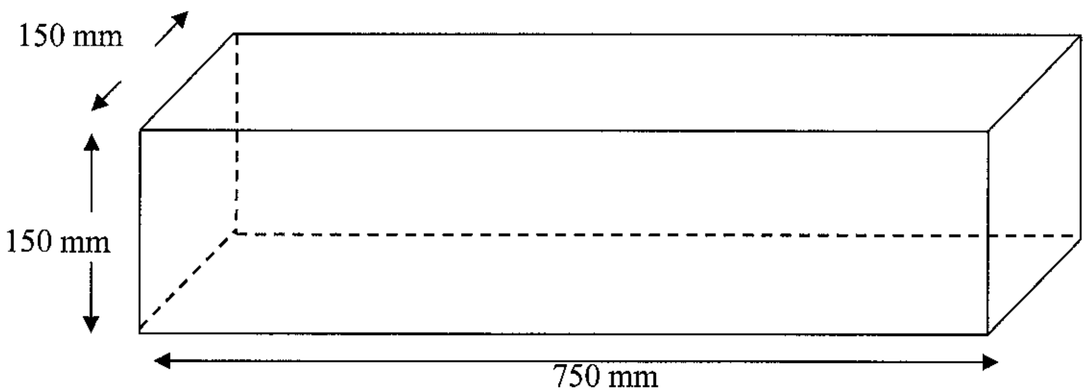

Figure 3-4: Control Beam Dimension

Two more beams were externally reinforced by CFRP with similar length and width which is 750 mm and 150 mm. The thickness of the CFRP laminates used was 1.2 mm for the first semester (Refer to Figure 3-5)

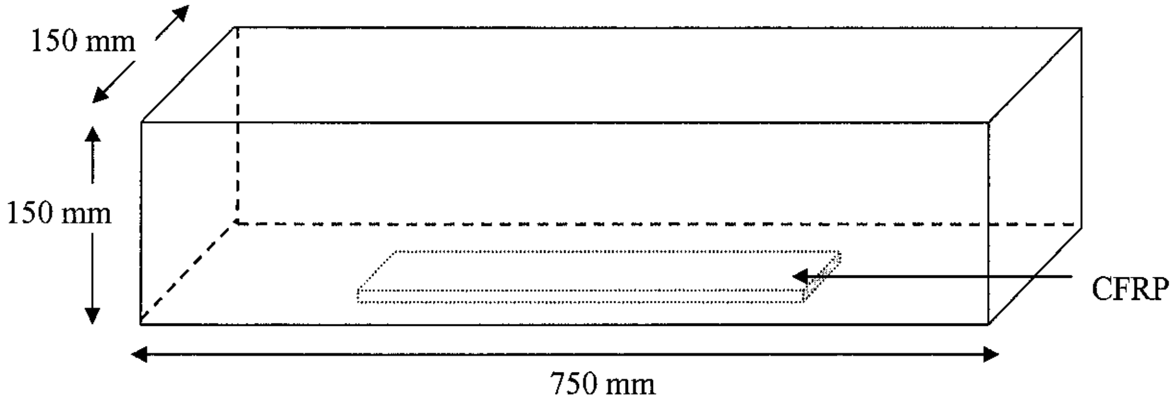

Figure 3-5: R.C Beam Dimension

The concrete flexural capacity test for the r.c beams required the strength of the concrete at 28 days. For the first semester, the two beams were tested under static loading. The testing of the flexural capacity of the r.c beams was done using the Static Crushing Machine. Sika Carbodur 1012 plates and Sikadur-30 adhesive were used for the strengthening and rehabilitation of the r.c beams. It is to determine the behaviour of the r.c beam strengthened by CFRP externally under fatigue loads. The mixture content of the concrete that was used to produce two beams and cubes was shown in Table 3-2:

Table 3-2: Mixture Content of Beam

Material	Mix ratio (by weight)	Mix ratio (%)	Kg/m^3	Kg
Cement	1	13.6	327	24.53
Sand	2.3	31.29	752	56.40
Course aggregate	3.5	47.60	1145	85.88
Water	0.55	7.48	180	13.5

3.1.4 Fatigue Analysis of R.C Beams with CFRP

For fatigue analysis, dynamic universal testing machine was used. The standard concrete sample of 150mm x 150mm x 750mm was subjected to loading and unloading process until the sample was failed. The arrangement was based on flexural strength testing as according to ASTM C293 and thus centre loading to the beam was employed.

Due to the inability to use the larger dynamic universal testing machine, a smaller dynamic universal testing machine was setup and used for the testing. As a result, discrepancies must be included for setting the max displacement of r.c beam which was in this case, the max displacement at the upper level and lower level was set at ±5mm. Excluding the discrepancies for displacement, the cyclic displacement set should account for 70%-80% (0.56mm to 0.64mm) of the max displacement of the beam. As for frequency for the loading and unloading cycle, it was set at 5Hz to allow sufficient to monitor the response of the beam. The maximum cycles set was 2000 cycles.

The present equipment available in the laboratory only permits the generation of load against displacement graph unlike more commonly used graph of stress-strain curve and S-N curve.

3.2 Tools and Equipment

The tools and equipment were needed in the process of producing the beams and testing work.

3.2.1 Universal Testing Machine

The universal testing machine (UTM) was used during the static load test (Refer to Figure 3-6)

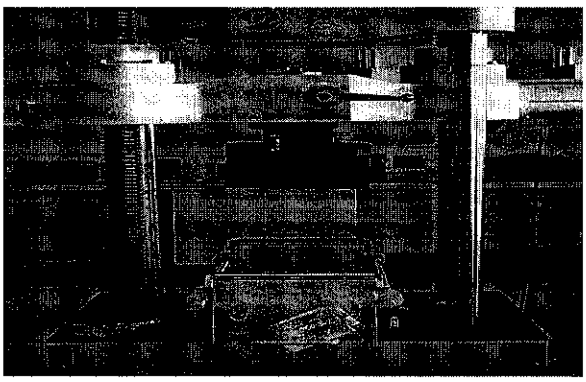

Figure 3-6: Universal Testing Machine

3.2.2 Destructive Test Machine

This machine was used to test the compressive strength of the concrete cubes which was produced from the same materials of the beams. This is a method to determine the compressive strength of the beams (Refer to Figure 3-7).

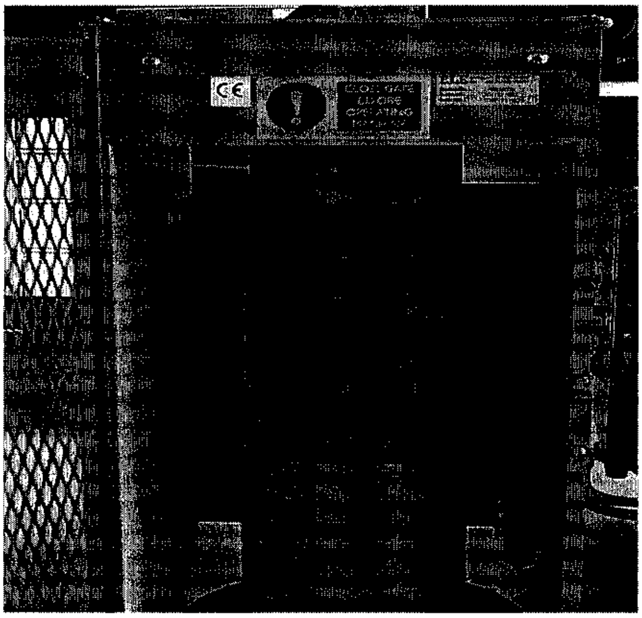

Figure 3-7: Destructive Test Machine

3.2.3 Beam Moulds

The beam moulds were used during the process of beam casting. The size of the beam moulds is 150 mm x 150 mm x 750 mm (width x depth x length) (Refer to Figure 3-8).

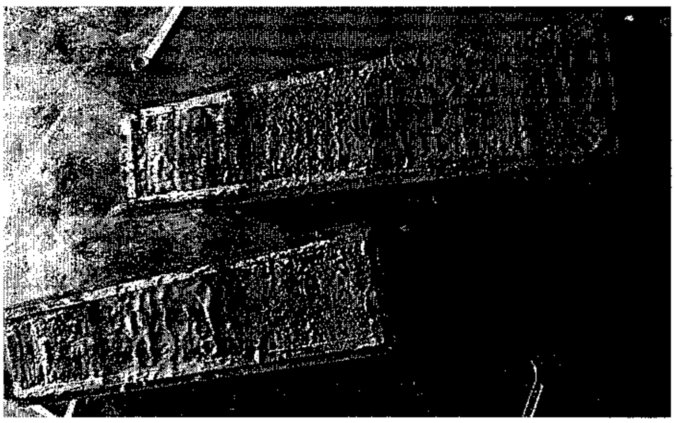

Figure 3-8: Beam Moulds

CHAPTER 4

RESULTS AND DISCUSSION

4.1 Static Test

4.1.1 Control Beam

As the static load from the universal testing machine was applied to the center support of the beam, the cracks of the beam began to appear at the centre support, forming from the top to the bottom (Refer to Figure 4-1).

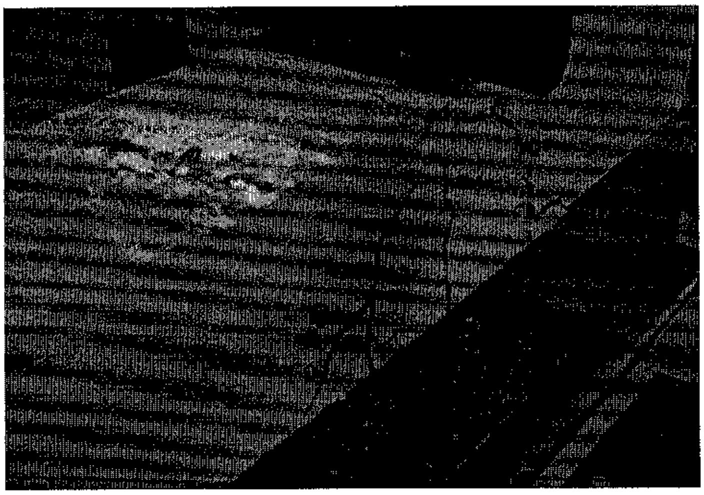

Figure 4-1: Crack Flow of Control Beam

Conventional ductile flexural failure due to yielding of the internal tensile steel reinforcement at the centre support of the beam was occurred (Refer to Figure 4-2). The displacement of concrete due to the crack lines was seen clearly.

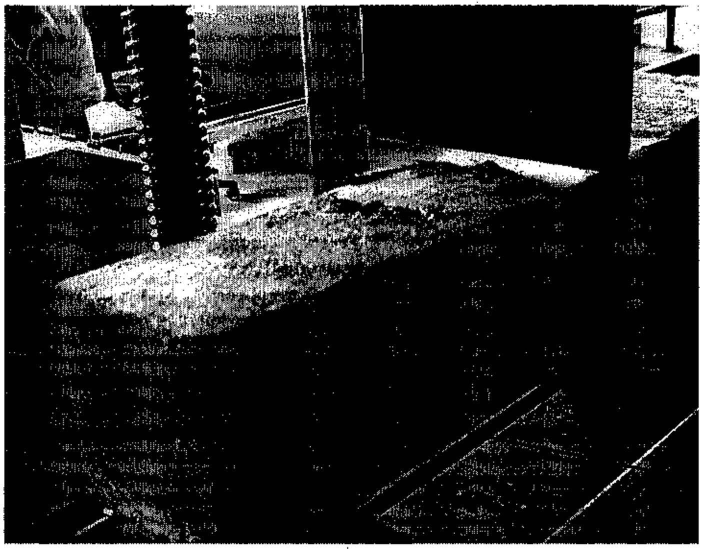

Figure 4-2: Control Beam Failure

The maximum load that the control beam resisted was 83.35 kN with a stress of 28MPa. (Refer to Figure 4-3).

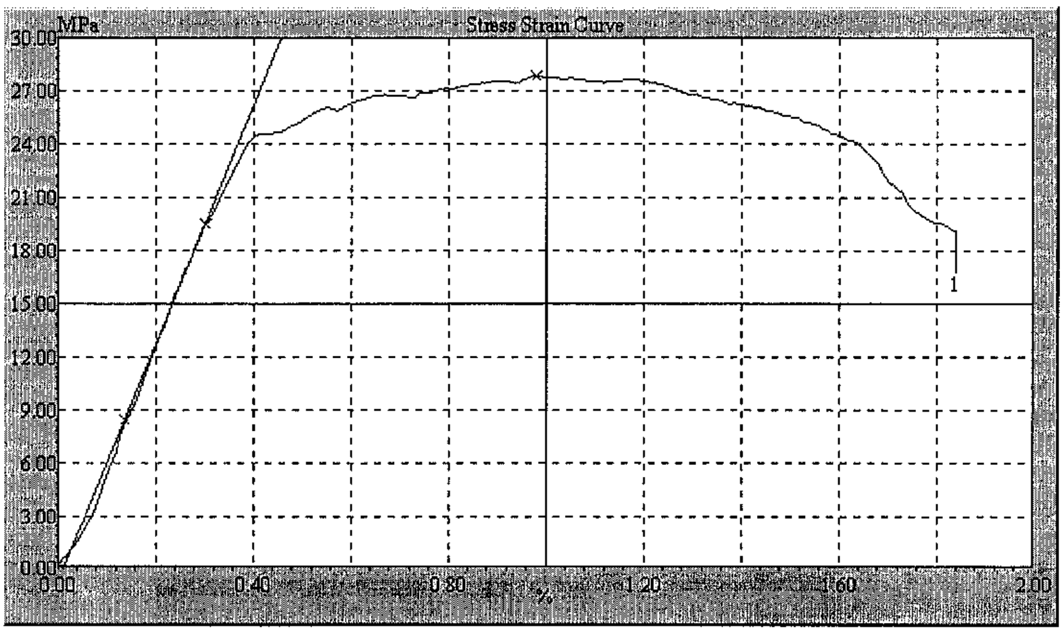

Figure 4-3: Graph of Stress-Strain Curve for Control Beam

4.1.2 R.C. Beam with 1.2mm CFRP Laminates

The loading was applied to the center of the beam (Refer Figure 4-4).

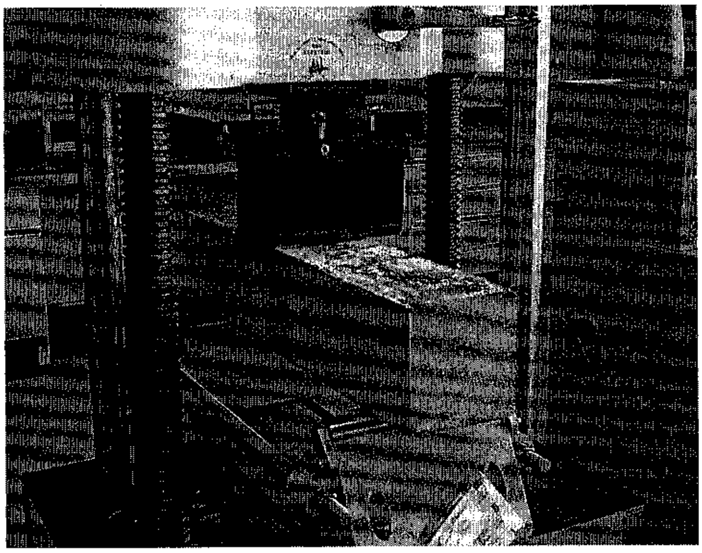

Figure 4-4: Initial Setup for R.C beam with 1.2mm CFRP

Once the static load was applied, a sudden noise of breakage occurred. This was analyzed and determined that part of the CFRP laminates was peeled off from the concrete surface (Refer to Figure 4-5).

Figure 4-5: Crack Flow of R.C beam with 1.2mm CFRP

The crack lines and the displacement of the concrete was obviously seen due to the crack increase as the static load being applied continuously. The delamination of the CFRP laminates caused the beam to have a serious ductile flexural failure due to the yielding of the internal tensile steel reinforcement followed by concrete crushing at the centre support of the beam (Refer to Figure 4-6).

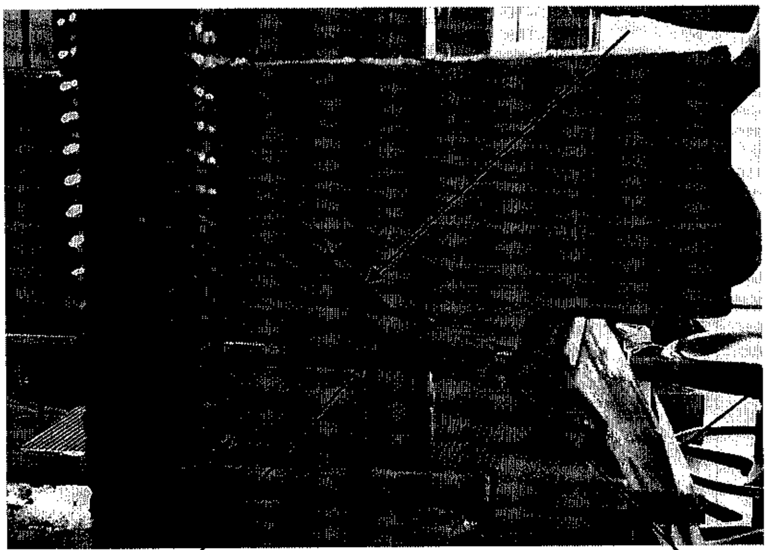

Figure 4-6: R.C beam with 1.2mm CFRP Failure 1

Figure 4-7: R.C Beam with 1.2mm CFRP Failure 2

The delamination of CFRP laminates due to the bonding failure of the epoxy adhesive to the concrete beam had caused serious failure to the particular part of the beam. It was seen that the beam had a displacement in the horizontal alignment of the beam due to yielding of the internal tensile steel reinforcement (Refer to Figure 4-8).

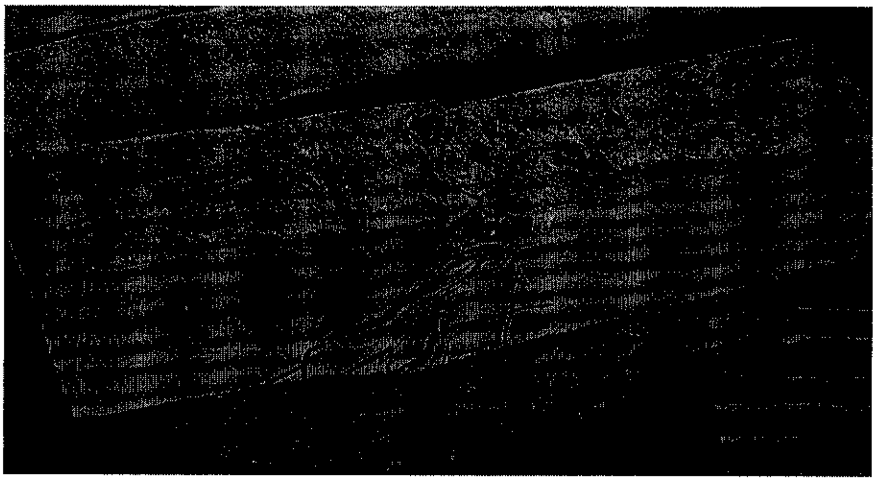

Figure 4-8: R.C Beam with 1.2mm CFRP Failure 3

The maximum load that r.c beam with 1.2mm CFRP can resist was 74.44 kN with a stress of 23.5 MPa. (Refer to Figure 4-9).

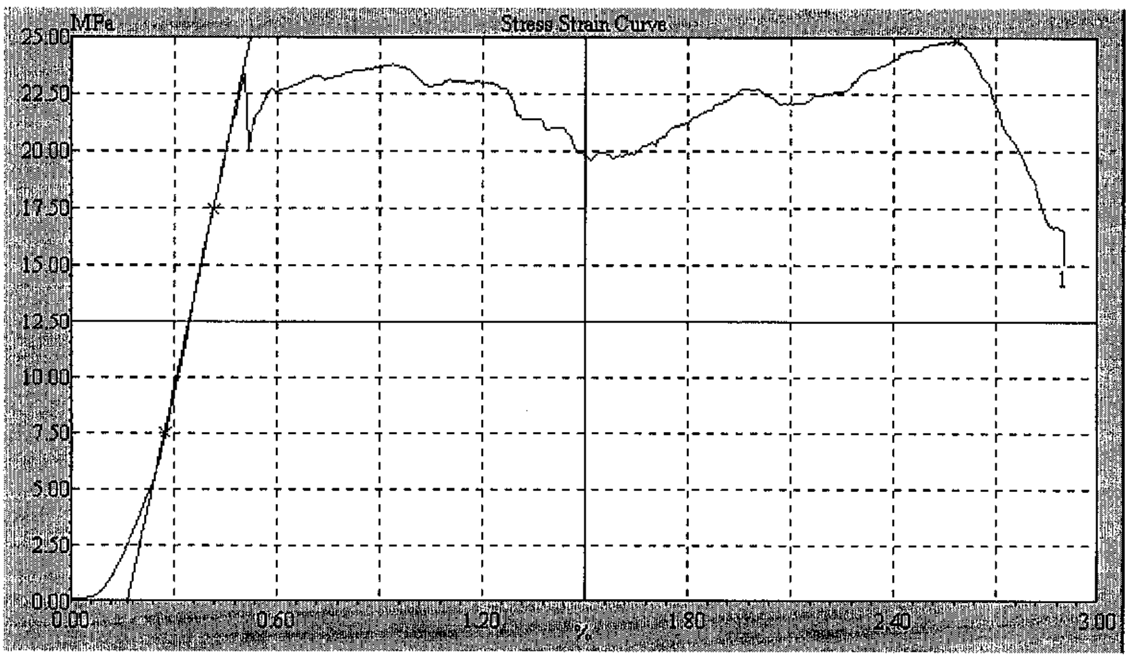

Figure 4-9: Graph of Stress-Strain Curve for R.C Beam with 1.2 mm CFRP

The beam was reinforced with the CFRP externally only at the bottom of the beam. It is because during the deflection, the bottom area has to provide more resistance against the load compared to the top area of the beam. The details of the test specimen were shown in Table 4-1.

Table 4-1: Details of the Test Specimen

Beam no.	Main longitudinal steel		Form of CFRP	Top CFRP over central support		Bottom CFRP at midspan	
	Top	Bottom		Type	Length	Type	Length
Control beam	2T12	2T12	-				
R.C beam with 1.2 mm CFRP	2T12	2T12	plates	-	-	1012	500mm

Comparison of r.c beams was simplified in the table below. (Refer Table 4-2). The major failure of r.c beams with 1.2mm CFRP is due to debonding of CFRP laminates and concrete surface.

Table 4-2: Results of the Test Specimen

Beam no	Behaviour of R. C beam	Static load, P_u (kN)	Stress (MPa)
Control beam	Conventional failure	83.35	28.0
R.C beam with 1.2 mm CFRP	Bonding and Peeling failure	74.44	23.5

4.2 Fatigue Test

4.2.1 R.C Beam with 1.4 mm CFRP Laminates

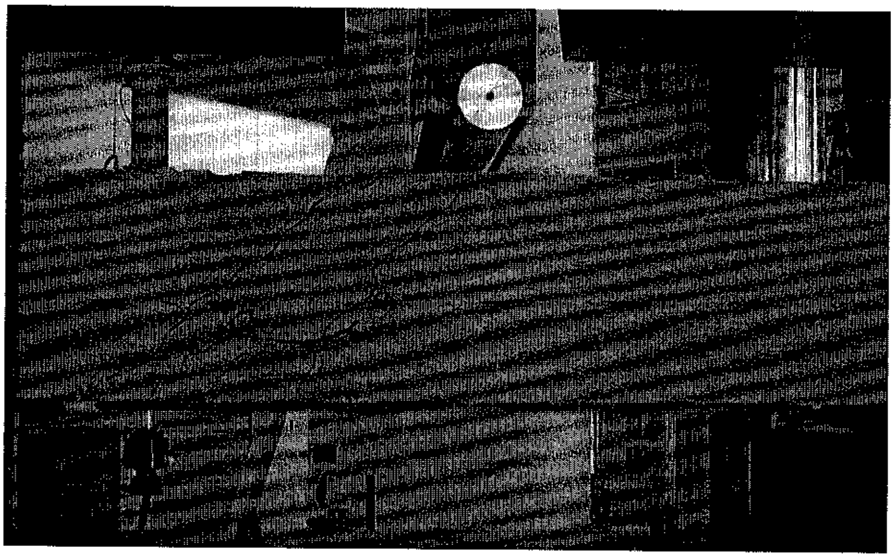

Figure 4-10 R.C beam with 1.4 mm CFRP

From the picture above, the crack lines appeared on the beam is due to failure in shear whereby the crack lines initiated from the centre to the edge of the beam. This is because the r.c. beam with 1.4mm CFRP is designed to strengthen the r.c. beam in bending which is very high in flexural strength. The r.c beam is still very tough although it had been applied to a maximum of 2000 cycles. Thus, in other words, the beam can further cater the loading and unloading process even after 2000 cycles. In addition, the CFRP plate is still strongly attached to the beam surface bonded with Sikadur-30 epoxy adhesives.

4.2.2 R.C Control Beam

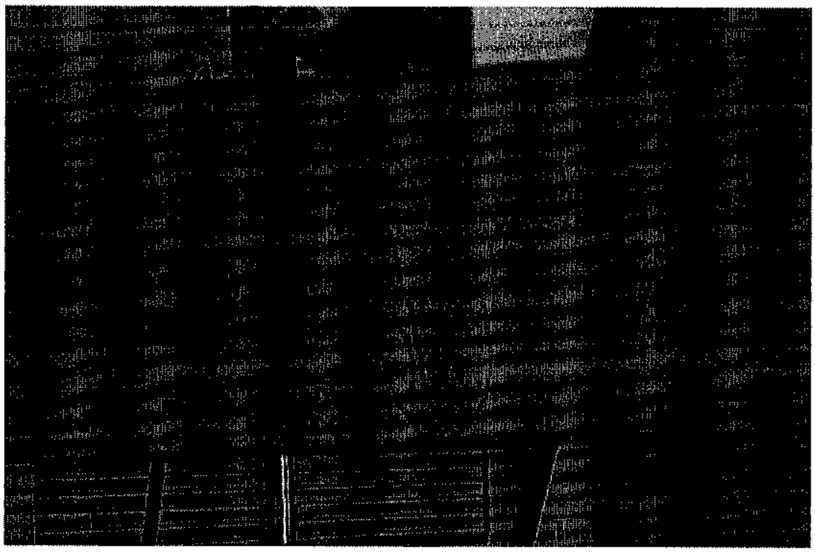

Figure 4-11: R.C. Control Beam

As for r.c. control beam, a sudden noise was heard immediately once the cyclic load was applied on to it. The crack lines formed was obviously seen at the centre part of the beam whereby the mode of failure is due to bending failure which is low in flexural strength. The first crack lines width became wider and wider throughout the application of fatigue loads of a maximum of 2000 cycles. The crack width was about 2.5 to 3 mm. Other crack lines were seen at the edge of the r.c control beam which indicated that the r.c control beam has very low strength in shear. Thus, without the application of CFRP laminates, it was clearly seen that crack lines appeared at once at the centre of the r.c control beam which is due to bending followed by shear failure.

4.2.3 R.C Beam with 1.2 mm CFRP Laminates

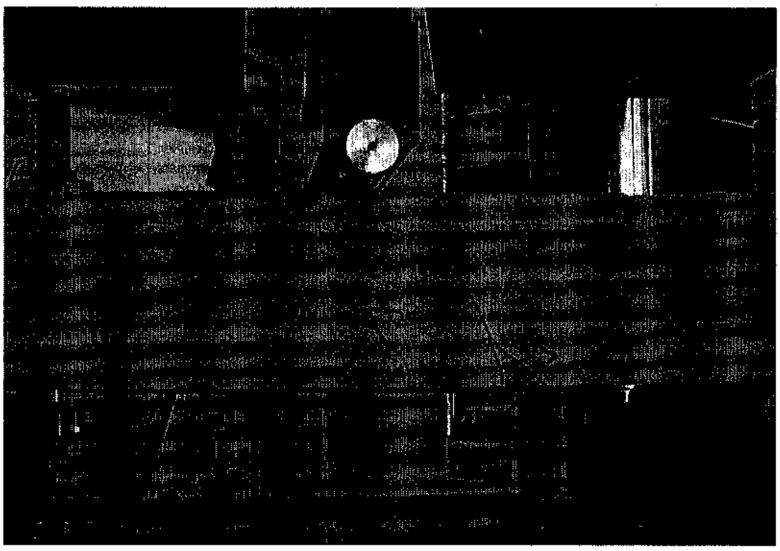

Figure 4-12: R.C Beam with 1.2mm CFRP

From the picture above, it showed that the crack lines formed at the centre of the beam which caused by failure in flexural strength and crack lines at the side of the beam which is due to shear failure. This is because the capacity of 1.2mm thickness of CFRP is insufficient to cater the load due to bending as well as shear under the loading and unloading process. However, the beam did not break or rupture although the loading and unloading process was carried out through a maximum of 2000 cycles. The 1.2 mm CFRP laminates was seen partly delaminated at the right of the r.c beam. This may happened due to some factors which include debonding of CFRP laminates and concrete surface due to the thickness of Sikadur-30 epoxy adhesives applied and inaccurate method of application. It may also due to the insufficient thickness of CFRP laminates.

4.3 Static

From the experiment, r.c beam with 1.2mm CFRP that was strengthened with the CFRP laminates showed a lower flexural capacity value as compared to the control beam. The major cause to the lower flexural capacity value is due to the debonding of epoxy adhesives to the concrete surface at part of the beam. The failure modes however did not cause complete collapse of the beam. Thus, it showed that the CFRP laminates prevented or acted as obstacle to prevent the beam to collapse and enhance the flexural strength of the beam on the other part of the beam whereby the CFRP laminates is still bonding firmly with the beam surface.

Control beam experienced the concrete crushing failure and yielding of reinforcement. The beam failure occurred through the center of the midspan. It is because the control beam did not reinforced with CFRP laminates and the concrete crushing concentrated at the centre of the beam and continued to fail through the area.

R.C beam with 1.2mm CFRP experienced the concrete crushing failure, bonding failure and peeling failure. The load concentrated on the area which is not reinforced by the CFRP laminates; whereby delamination of the CFRP laminates occurred caused bonding and peeling failure. On the other hand, there were no cracks found on the other part of the beam which reinforced by CFRP.

By referring to Figure 4-9; from the early stage of the stress-strain curve, the static load began to decrease once the ultimate strength of the beam was achieved. However, after the drop, there was an increased of gradient until an ultimate strength higher than the previous result was obtained. Thus, this proved that the major failure of part of the beam is due to delamination of CFRP laminates to the beam.

Thus, due the delamination of CFRP and the insufficient thickness of epoxy adhesives, the usage of CFRP laminates to enhance the flexural capacity of the beams due to static test is unsuccessful.

4.4 Fatigue

A dynamic testing machine with the configuration of machine settings as mention in section 3.1.4 was used to test on r.c beams with beam mould of 150mm x 150mm x 750mm. The result for fatigue testing showed in Figure 4-13, Figure 4-14 and Figure 4-15. From the figures, it can be seen that the lines situated closely at each cycles. The lines which oriented to the left of the graph are actually the loading process while the lines which oriented to the right of the graph are the unloading process. The total cycles of loading and unloading until failure of the r.c beams occur is 2000 cycles which cannot be seen on the graph.

By referring to Figure 4-13, it showed the loading and unloading lines for r.c beam with 1.4mm CFRP. From the graph, the maximum tension load is 70 kN. As for deformation, the maximum and minimum value is 2.90 mm and 1.88 mm respectively. Based on Figure 4-14, the maximum tension load of fatigue loading on r.c control beam is 23 kN. The maximum and minimum deformation value is 2.91 mm and 1.86 mm. As for Figure 4-15, the maximum load in tension is 35 kN. The maximum and minimum deformation for r.c beam with 1.2 mm CFRP laminates is 2.89 mm and 1.86 mm.

As a result, the r.c beam with 1.4 mm CFRP laminates had sustained and cater the highest load, 70 kN; as compared to control beam and r.c beam with 1.2 mm CFRP laminates under the process of loading and unloading of 2000 cycles. Initially, where no cracks initiated, it took approximately 70 kN to displace the beam to 2.90 mm with allowance for discrepancies. After repeated cycles which triggered the initiation of cracks, less force required to displace the beam to 2.90 mm whereby the deformation dropped to 1.88 mm after 2000 cycles. This drop in displacement force imposed indicated that weak plane in the r.c. beam was formed. However, small deviation of deformation did not cause failure to all r.c beams even though after 2000 cycles.

Basically, the cyclic loading imposed on r.c beams resisted by the tensile action at the lower section of the r.c beam. Since flexural strength is a measure of tensile strength in concrete, flexural strength will be a good representation of tensile loading that concrete can withstand. Concrete that has higher flexural strength will have higher fatigue resistance.

Judging from the three graphs due to fatigue test, flexural strength of r.c beam with CFRP laminates and without laminates, it can be deduced that r.c beams with 1.4 mm CFRP laminates has some degree of fatigue resistance as compared to r.c beams with 1.2 mm CFRP and r.c control beam. It took 2000 cycles with its maximum flexural strength at 28 days and with 1.4 mm CFRP laminates which eventually only caused crack lines to appear at the edge of the beam which happened due to shear failure. However, there is no sign that indicates failure of the r.c beam with 1.4 mm CFRP since the beam is still intact and with the CFRP laminates attached to it. In other words, the beam can sustained more than 2000 cycles of fatigue loading. This fatigue resistance property can be attributed to the strong bond formed in the concrete matrix and the effectiveness of Sikadur-30 epoxy adhesive that strongly bond the CFRP laminates to the beam surface which enhancing the flexural strength.

Thus, obviously r.c beam with 1.4 mm CFRP laminates has a higher flexural strength as compared to r.c beam with 1.2 mm CFRP laminates. This is because 1.4 mm CFRP laminates has greater capacity as compared to using 1.2 mm CFRP laminates. On the other hand, as a comparison to control beam, r.c control beam showed an immediate failure in bending followed by shear. The crack lines become wider during the loading and unloading process, which is about 2.5 mm to 3.0 mm.

The fatigue characteristics are different for each of the r.c beams. Under the loading of 2000 cycles, the r.c beam with 1.4 mm CFRP showed crack lines at the edge of the r.c beam. Throughout the loading and unloading process, only a few crack lines appeared with no indication of breakage. The crack lines which only appeared at the edge which indicated as shear failure. In addition, the CFRP laminates still well attached to the beam surface without peeling failure or debonding failure. As for r.c control beam, once the loading and unloading process began, there was a sudden noise of crack lines breakout at the centre of the beam which then followed by crack lines which eventually occurred at the edge of the beam. Furthermore, the crack lines at the centre of the beam became wider and wider during the experiment. Thus, it showed that r.c control beam is very weak in bending followed by shear failure since there is no CFRP laminates to strengthen and enhance the beam.

The fatigue life of the beams tested generally sustained a maximum of 2000 cycles since there is no rupture or breakage of the beams. As a result, the r.c beam with 1.4 mm CFRP laminates can sustained the loading and unloading process even more than 2000 cycles. However, theoretically the fatigue life of r.c control beam maybe lesser as compared to r.c beam with 1.4mm CFRP since the r.c control beam already had crack lines of 2.5 mm to 3mm wide at the centre of the beam. Continuous application of loading and unloading after 2000 cycles may caused the beam to break easily as compared to r.c beam with 1.4 mm CFRP whereby the beam is still well intact and the CFRP laminates is still strongly bonded to the beam surface.

The behaviour of r.c beam showed that r.c beams without CFRP laminates had weaker strength in both bending and shear since it showed crack lines both appeared at the centre and at the edge of the beam. With the application of CFRP laminates, the r.c beam is strong in bending but weak in shear since crack lines was seen appeared at the edge of the beam. Moreover, the crack lines of the r.c control beam became wider and wider at approximately 2.5 mm to 3.0 mm at the centre of the beam. Thus, r.c beam is strong in bending when CFRP applied externally on to the beam.

From the results obtained, the higher the capacity of CFRP, the greater the strength to strengthen reinforced concrete structures and rehabilitate of structurally deteriorated or functionally obsolete reinforced concrete structures. In addition, by using CFRP laminates with r.c beam, it sustained a longer fatigue life as compared to r.c beam and beam without reinforcement. This is also best apply to bridge strengthening where it can easily deteriorate and damage by overweight vehicles that passing to and fro on the bridge which in turn causes loading and unloading effects on to the bridge.

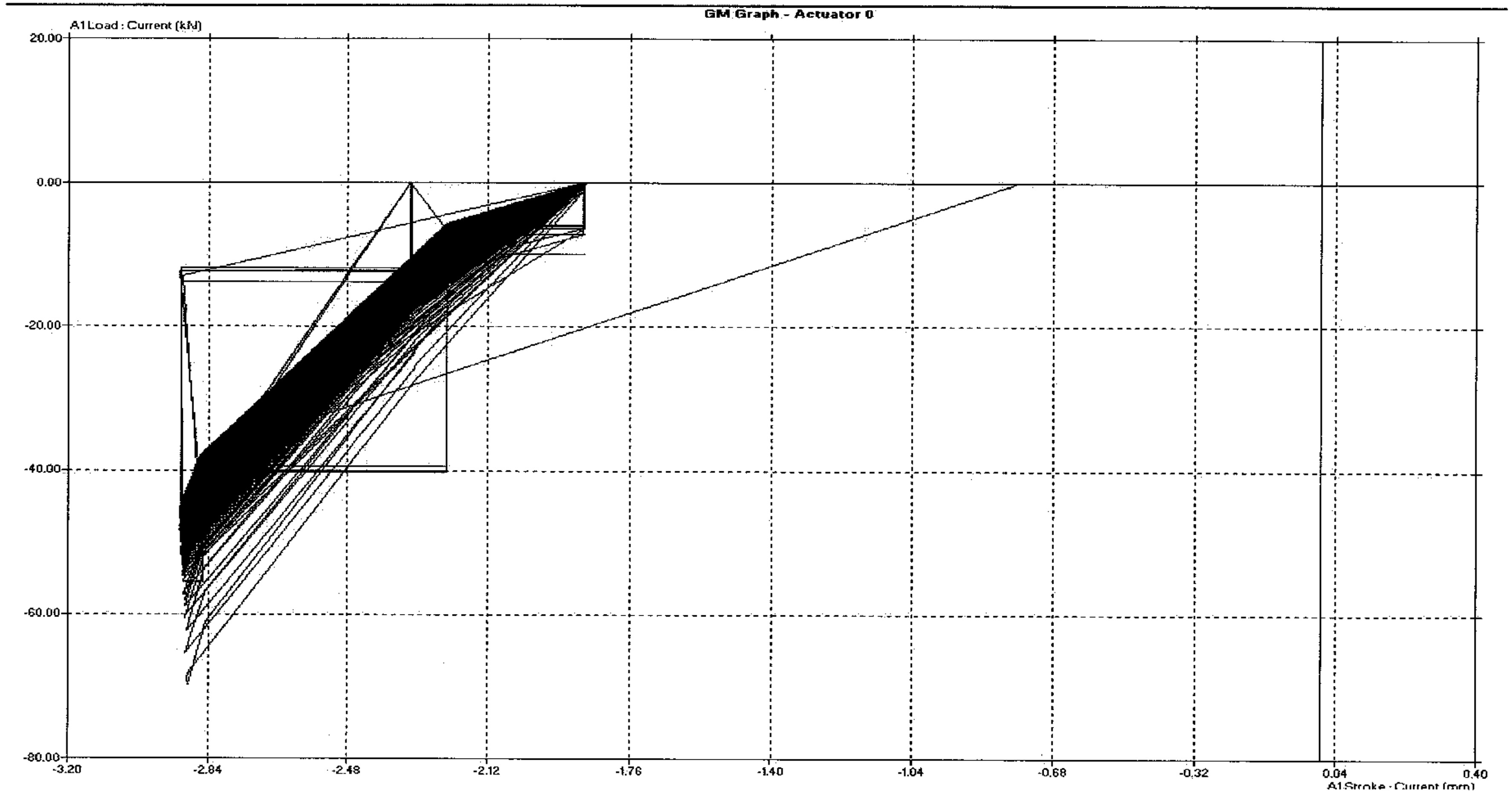

Figure 4-13: Graph Of Cyclic Load for R.C Beam with 1.4mm CFRP

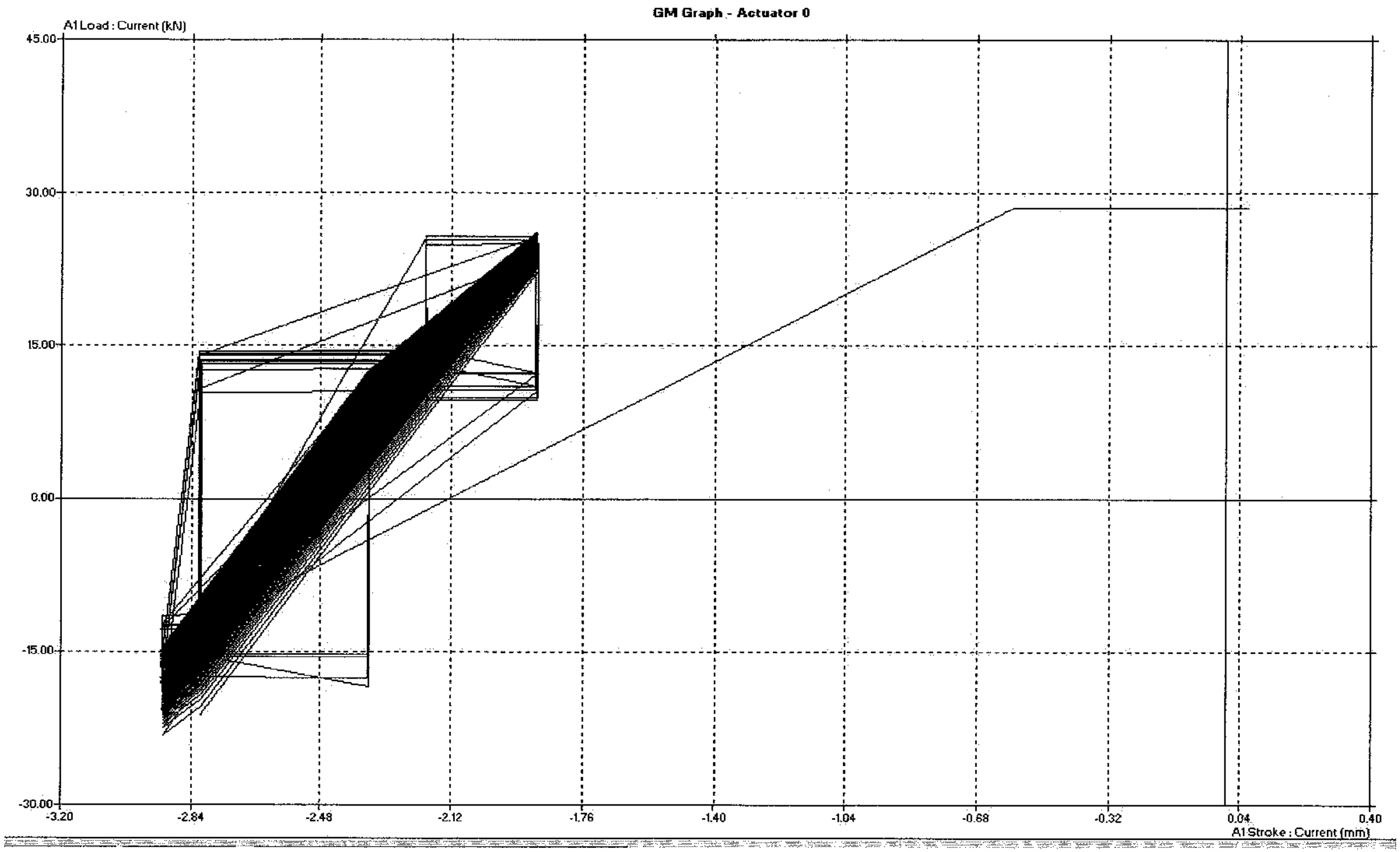

Figure 4-14: Graph Of Cyclic Load for R.C Beam Control Beam

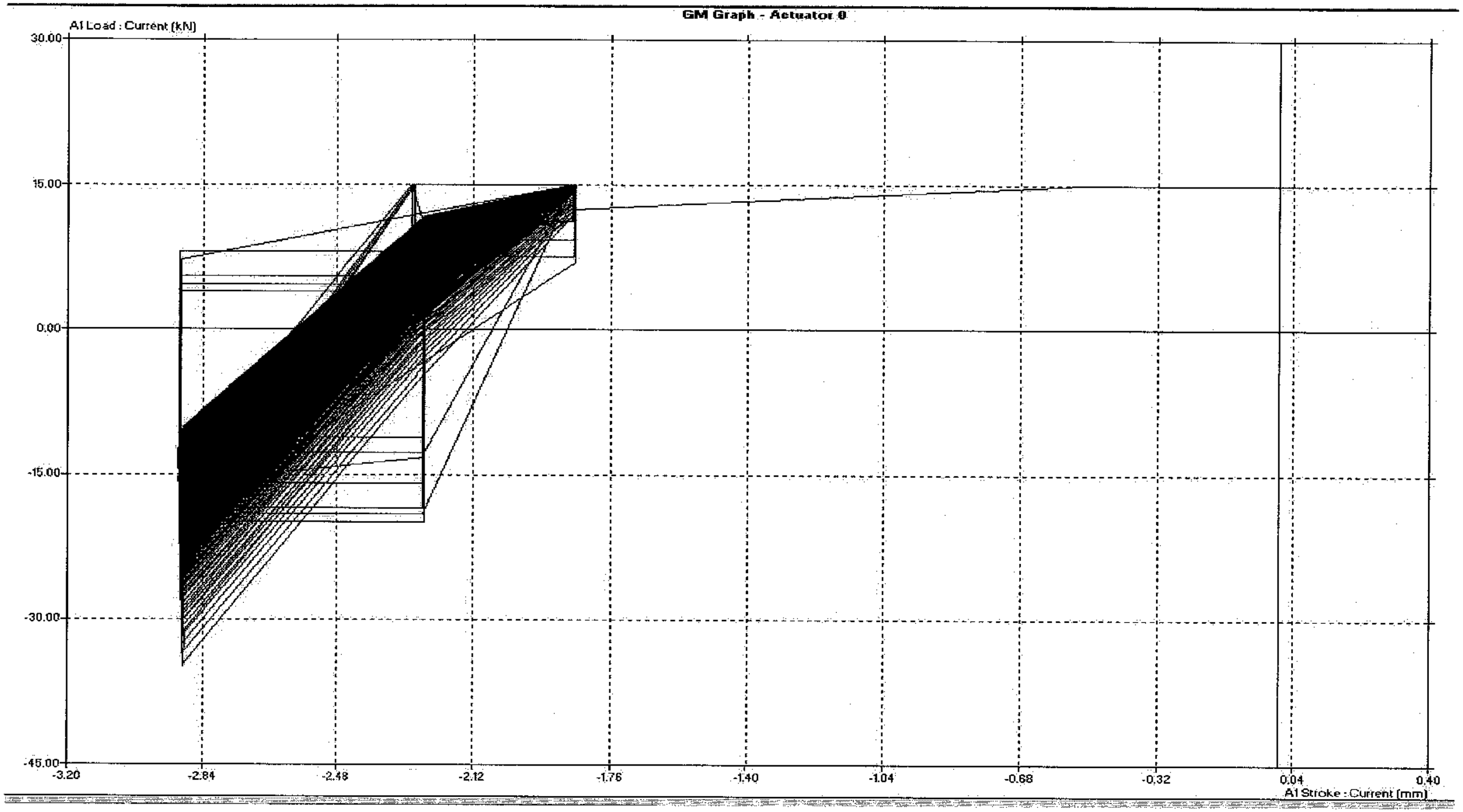

Figure 4-15: Graph Of Cyclic Load for R.C Beam with 1.2 mm CFRP

CHAPTER 5

CONCLUSION AND RECOMMENDATION

There are two general failure modes of beams with external applied CFRP laminates under static loading which are laminate separation and peeling failure of the concrete cover attached to the laminates. From the experiment, the static load of r.c control beam is higher than the r.c. beam with 1.2mm CFRP. This happened due to the bonding failure of the epoxy adhesive to the concrete which then causes peeling in concrete. Thus, in this case the application of CFRP laminates in order to enhance the flexural capacity of the beam due to static test is unsuccessful.

The experimental results for fatigue loading had been analyzed. The capacity of CFRP determines to strengthen r.c beams is 1.4mm instead of 1.2 mm laminates. The greater the capacity of CFRP used, the greater the flexural strength of the beam. The fatigue life of the r.c beams can sustain a maximum loading and unloading of 2000 cycles or more. The behaviour of r.c beams strengthened by CFRP had been determined as compared to the control beam. R.C beam with 1.4 mm CFRP laminates indicates failure in shear whereas control beam has failures in both bending and shear. The fatigue characteristics of r.c beam were analyzed through crack lines initiated throughout the fatigue load application. Thus it proved that CFRP has enhanced and strengthened the r.c beams in bending.

As for recommendation, the cement bags should be stored in an air tight container or air tight room to ensure the cement properties is controlled. This is because the cement bags stored in an air-condition environment may cause cement hardening and eventually affect the concrete properties.

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18. Perry S. Green, Andrew J. Boyd, *"CFRP Repair of Impact-Damaged Bridge Girders: Volume I: Structural Evaluation of Impact Damaged Prestressed Concrete I Girders Repaired with FRP Materials"*, (January 2005)

19. Sherif El-Tawil, Cahit Ogunc, Ayman Okeil, Mohsen Shahawy, Member, ASCE, *"Static and Fatigue Analyses of RC Beams Strengthened With CFRP Laminates"*, Journal of Composites and Construction, (November 2001), 258-267

20. Heinz Meier, Reto Clenin, Miklos Basler, *"Bridge Strengthening With Advanced Composite Systems"*

21. http://www.cif.org/, R.J.Carr, "*Construction Innovation Forum*" (2004)'

22. http://www.designinsite.dk/htmsider/m0632.htm, Carbon fiber, 1997, 1998, Torben Lenau

23. Sika Carbodur, *Construction*, revised July 2002, product data sheet, 1-4

24. Solutions With Sika System, *"Technology and Concepts for Sika Carbodur Structural Strengthening Systems"* 1-11

25. Solutions With Sika System, *"Shear Strengthening: Sika Carbodur Composite Systems"* 1-16

26. Properties of Concrete, A.M. Neville, Longman Publisher, 4th Edition, 1995

APPENDIX

Sika® CarboDur

REVISED JULY 2002

Heavy-Duty CFRP Strengthening System

DESCRIPTION

Sika CarboDur is a heavy-duty strengthening system for reinforced concrete and timber. It consists of two components: Sikadur-30 adhesive for bonding reinforcement and Sika CarboDur-laminates.

USES

The Sika CarboDur System can be used to strengthen reinforced concrete and timber structures due to:
- Loading increases.
- Damage to structural parts.
- Serviceability improvements.
- Change in structural system.
- Design or construction defects.

ADVANTAGES

- Low in weight.
- Available in any length.
- Low overall thickness.
- Easy to transport.
- No preparation of Sika CarboDur-laminates.
- Laminate intersections are simple.
- Economical application – no heavy handling and installation equipment.
- Very high tensile or flexural strengths can be achieved.
- High modulus of elasticity.
- Outstanding fatigue resistance.
- Can be coated without preparation.
- Alkali resistant.

STORAGE AND SHELF LIFE

When not exposed to direct sunlight, Sika CarboDur-laminates have unlimited shelf life. Sikadur-30, when stored in the original sealed containers within the temperature range of +5°C to +25°C will keep for a minimum of three years.

INSTRUCTIONS FOR USE

Surface Preparation
The concrete or timber surface must be clean and free from grease and oil, dry, and have no loose particles or laitance.
This can be prepared by blast cleaning, scabbling or grinding. The concrete age should be 3 to 6 weeks minimum, depending on thickness, curing conditions, etc.
The surface to be coated must be level, with steps and form work marks not greater than 0.5 mm.
After cleaning remove all dust from the surface with an industrial vacuum cleaner.

Mixing
Sikadur-30 is supplied in factory proportioned units com-prising the correct quantities of Part A (Resin) and Part B (Hardener). Thoroughly stir both components separately using a slow running drill/stirrer with a helical paste mixer (max. speed 600rpm). Decant all Part B into Part A and mix thoroughly together until a uniform colour is achieved (typically 3 mins). A streaky colouration is indicative of inadequate or incomplete mixing. Apply immediately. Small units may be hand mixed provided an even colour is achieved.

Application
If any necessary patching work needs to be done on the surface, this must be done with Sikadur-41, on the day preceding the actual bonding operations.

Apply the well mixed Sikadur-30 adhesive carefully to the prepared substrate with a spatula to form a first layer of at least 1 mm. Place the Sika CarboDur-laminate on a table and clean it with Sika® Colma Cleaner. Apply the Sikadur-30 adhesive across the width of the laminate, ensuring a total coverage. The adhesive should be minimum 1 mm deep at each side, to minimum 2 mm deep at the centre. This is best done using a plastic spatula shaped on site to achieve this profile.
Within the open time of the adhesive, depending on temperature, place the Sika CarboDur-laminate onto the concrete surface. Using a roller, press the laminate into the epoxy material until the adhesive is squeezed out on both sides of the laminate.
Remove surplus epoxy adhesive. Samples should be made up on site to check the adhesive used in respect of curing rate and final strength. Measure the compressive bending and adhesive strength after curing. As a final check, test the laminates for drumminess by tapping lightly.
There is no need for mechanical equipment to press strips onto the substrate nor is it necessary to provide clamps or supportive devices to keep overhead strips in place.
Once cured the top of the laminates can be painted with a coating material such as Sikagard-62, Sikagard-670W or Sikagard-680S.

Cleaning
Clean tools immediately with Sika® Colma Cleaner. Wash hands and skin thoroughly in warm soapy water. Cured material can only be removed mechanically.

TECHNICAL DATA

A. SIKA CARBODUR-LAMINATES

Colour	Black		
Base	Carbon fibre reinforced with an epoxy matrix		
Apparent Density	1.6g/cm³		
Temperature Resistance	Between 150°C and 500°C.		
	Sika CarboDur S	**Sika CarboDur M**	**Sika CarboDur H**
Elastic Modulus	> 165,000 MPa	> 210,000 MPa	> 300,000 MPa
Tensile Strength*	> 2,800 MPa	> 2,400 MPa	> 1,300 MPa
Mean Value of Tensile*			
Strength at Break	3,050 MPa	2,900 MPa	1,450 MPa
Elongation at Break	> 1.7%	> 1.2%	> 0.45%
Packaging	Supplied in rolls of 250 m or palletised in pre-cut sections.		

* Mechanical values obtained from longitudinal direction of fibres.

Availability	**Type**	**Width mm**	**Thickness mm**	**Cross Sectional Area mm²**
Sika CarboDur S	Sika CarboDur S512*	50	1.2	60
	Sika CarboDur S612	60	1.2	72
	Sika CarboDur S812*	80	1.2	96
	Sika CarboDur S1012	100	1.2	120
	Sika CarboDur S1212	120	1.2	144
	Sika CarboDur S614	60	1.4	84
	Sika CarboDur S914	90	1.4	126
	Sika CarboDur S1214*	120	1.4	168
Sika CarboDur M	Sika CarboDur M614	60	1.4	84
	Sika CarboDur M914	90	1.4	126
	Sika CarboDur M1214*	120	1.4	168
Sika CarboDur H	Sika CarboDur H514	50	1.4	70

(*Readily available, other types available on demand.)

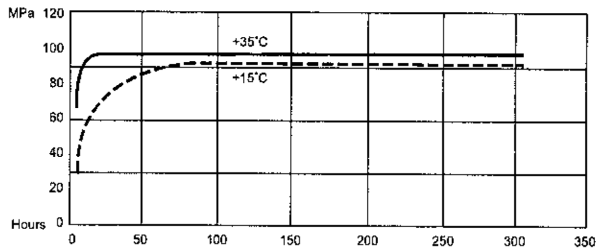
B. SIKADUR-30 ADHESIVE FOR BONDING REINFORCEMENTS

Appearance	Part A Part B Part A + B	White paste Black paste Light grey when mixed
Mix Ratio	A : B = 3 : 1	(parts by weight and volume)
Density	1.77 kg/L	(A + B)
Pot Life*	40 minutes	(at 35°C)
Open Time*	30 minutes	(at 35°C)
Sag Flow*	3-5 mm	(at 35°C)
Shrinkage*	0.04%	
Glass Transition Point*	62°C	
Static E-Modulus*	12,800 MPa	
Adhesive Strength (wet)*	4 MPa	(Concrete Failure)
Shear Strength*	15 MPa	(Concrete Failure)
Coefficient of Expansion	9×10^5 per °C	(-10°C to 40°C)
Packaging	5 kg tins	Part A 3.75 kg Part B 1.25 kg

* To F.I.P. Fédération Internationale de la Précontrainte
Note: The values given may vary according to amount of air entrained during mixing.

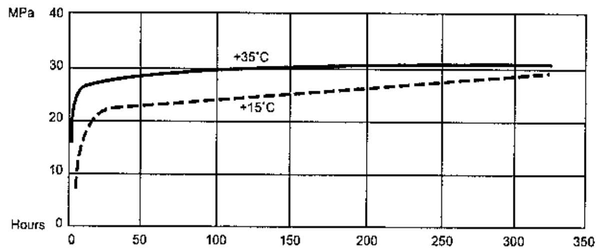
Compressive strength
(DIN 1154.7)

Development of compressive strength



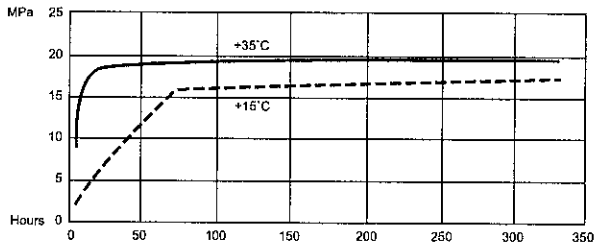
Tensile strength
(DIN 43455)

Development of tensile strength



Tensile slant shear strength (Sika Test)

Development of tensile slant shear strength



DESIGN NOTES

- A Sika CarboDur-laminate has no plastic deformation reserve.
- Maximum bending resistance of a strengthened section is reached when laminate failure occurs during steel yield and before concrete failure.
- Mode of failure is influenced by the laminate cross section.
- To limit crack widths and deformation the yield point should not be reached in the reinforcing bars under service conditions.
- Any shear cracks which occur must be prevented from causing displacement on the strengthened surface and shearing of the laminate.
- Stress and deformation calculations can be made by the normal methods.
- When assessing the condition of the structure, look at the dimensions, quality of existing construction materials, climatic conditions and agreed conditions of service.
- Design aspects to be verified in a Sika CarboDur Strengthening System:

Bearing safety
- non strengthened structure (total safety factor g≈1.2)
- strengthened structure (mode of failure mentioned above, check on strains)
- shearing of laminate must not occur
- anchorages

Fatigue resistance – check concrete and steel stresses

Serviceability
- deformation (with average strains, elasti behaviour of the structure and time-based strain changes in concrete)
- steel stresses (no plastic deformation in service conditions)
- limit crack widths (by limiting the steel stresses to less than the yield point under service conditions).

A full Sika Design Manual is available. Contact our Technical Department for details.

CONSUMPTION RATES

Laminate type	Sikadur-30
S512 / H514	~ 0.31 kg/m
S612 / S614 / M614	~ 0.38 kg/m
S812	~ 0.50 kg/m
S914 / M914	~ 0.56 kg/m
S1012	~ 0.62 kg/m
S1212 /S1214 / M1214	~ 0.74 kg/m

IMPORTANT NOTES

- Do not apply Sikadur-30 to surfaces with standing water. Maximum moisture content of the concrete 10%.
- Always mix a full kit to avoid mix ratio error.
- Only mix as much material as can be applied within the stated potlife.
- Do not dilute the product with solvent as this will affect the cure and in-service performance.
- Constant exposure to service temperatures >50°C may affect the performance of the product.
- Sika CarboDur can be firerated if required using standard fire rating materials.
- The temperature at which the Sikadur-30 is stored at during the 24 hours before it is mixed will govern its potlife when mixed.
- For shear strengthening, refer to SikaWrap technical data sheets.
- Compressive strengths, etc., of epoxy resins must be qualified by the testing method, eg. Test Standard or size of specimen under test and the rate at which the test piece is loaded under test, as these factors will affect the result markedly. Faster loading rates will generally give higher ultimate loads and vice versa. Also, a specimen at lower temperature will show higher strengths and vice versa.
- Sikadur-30 Parts A and B are a water pollutant and should not be discharged into drains, waterways or soil.

HANDLING PRECAUTIONS

- Avoid contact with the skin, eyes and avoid breathing its vapour.
- Wear protective gloves when mixing or using.
- If poisoning occurs, contact a doctor or the Poisons Information Centre.
- If swallowed, do NOT induce vomiting. Give a glass of water.
- If skin contact occurs, remove contaminated clothing and wash skin thoroughly.
- If in eyes, hold eyes open, flood with water for at least 15 minutes and see a doctor.

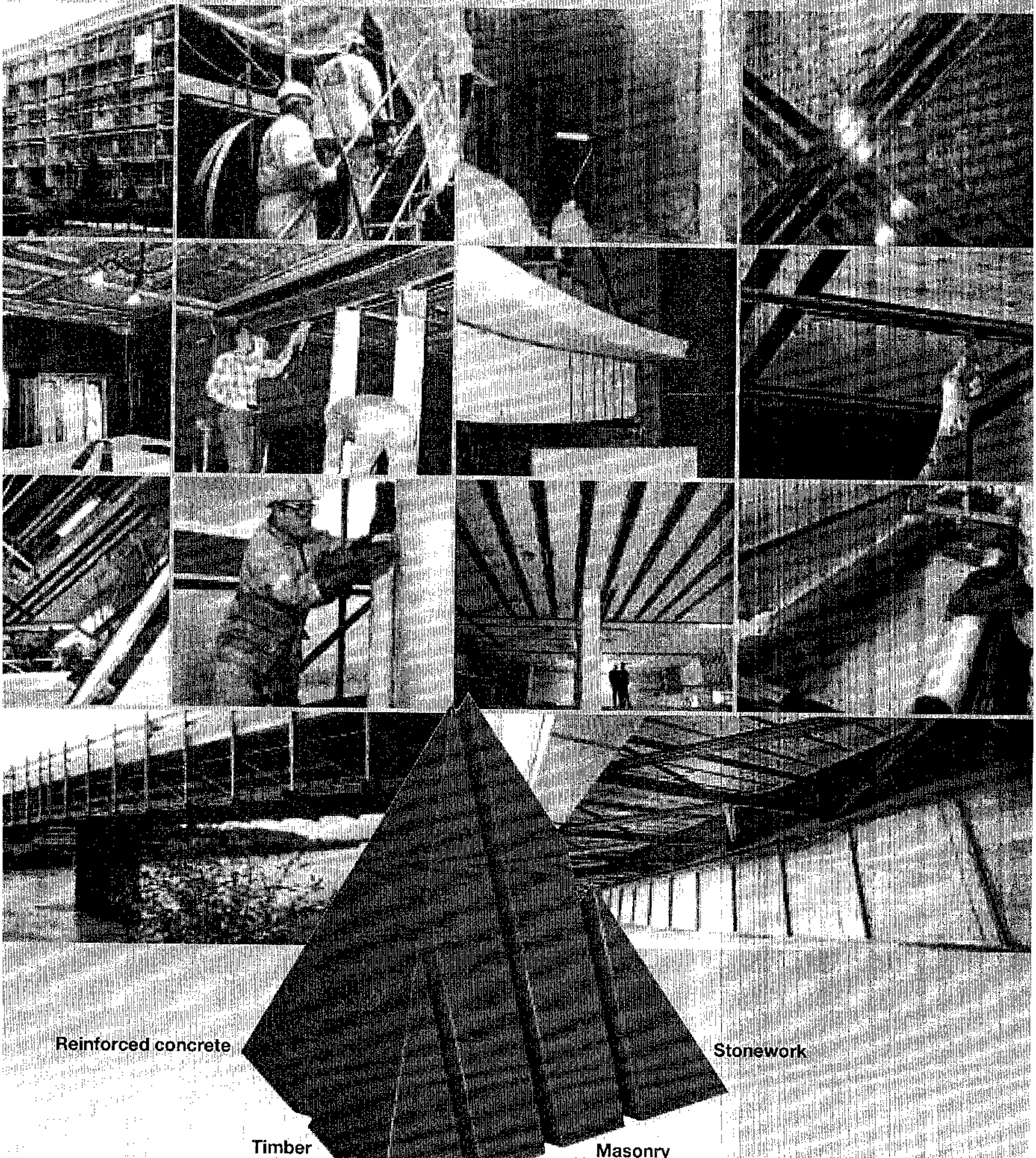
IMPORTANT NOTIFICATION

PLEASE CONSULT OUR TECHNICAL DEPARTMENT FOR FURTHER INFORMATION.

Sika Australia Pty Limited
ABN 12 001 342 329
55 Elizabeth Street
Wetherill Park NSW 2164
Tel: (02) 9725 1145
Fax: (02) 9725 2605
www.sika.com.au

Solutions with Sika Systems

echnology and Concepts or Sika® CarboDur® Structural trengthening Systems



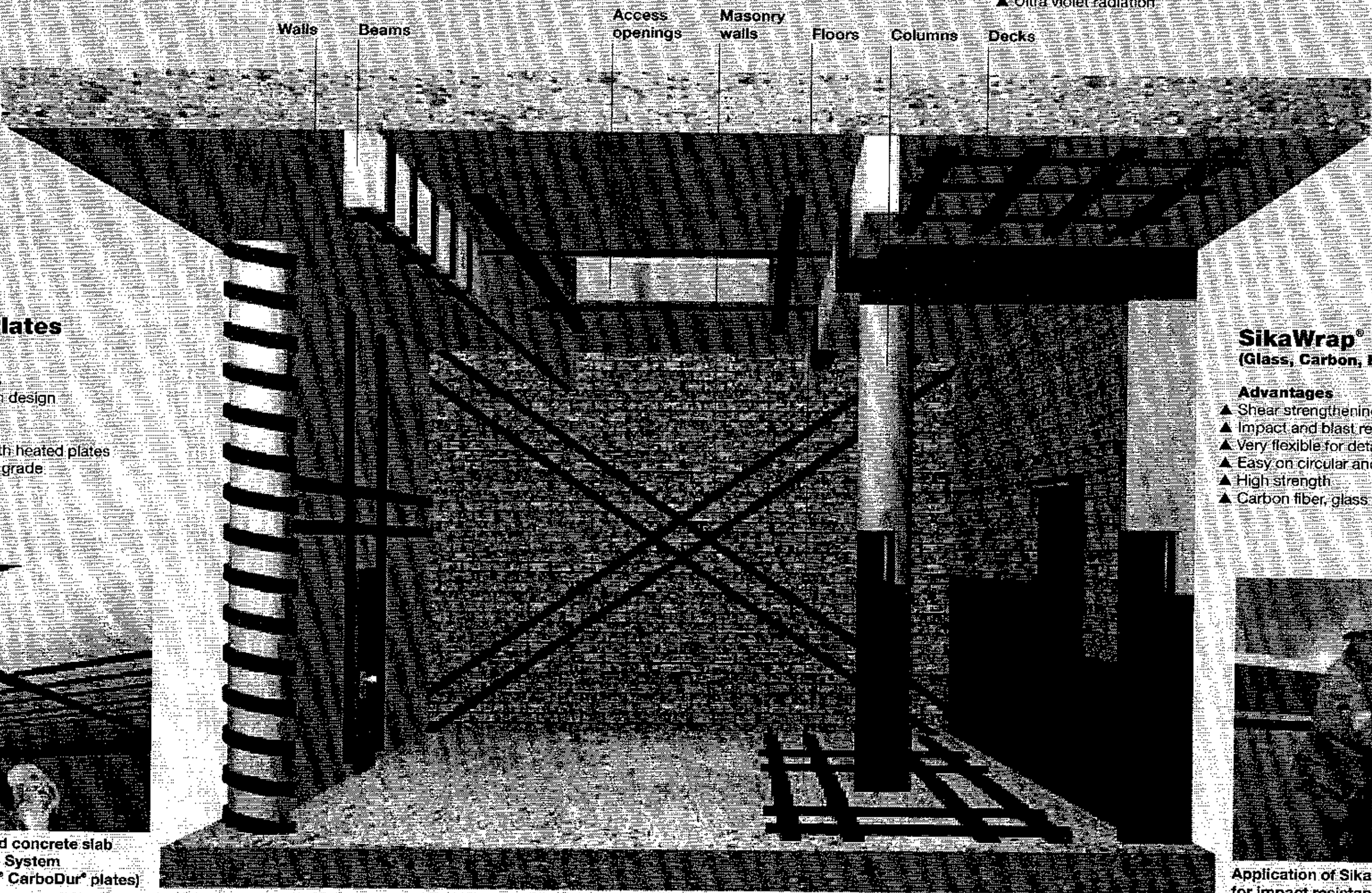
Strengthening System Requirements

Structural Requirements
- ▲ Static loading
- ▲ Dynamic loading
- ▲ Crack bridging
- ▲ Creep
- ▲ Durability

When the working load is applied, the plates absorb the tensile forces proportionally with the steel reinforcement. An unused load-bearing reserve must be available in the concrete compression zone of the existing structure. The adhesive layer must be capable of levelling out any stress peaks. The better the levelling, the greater is the proportion of load-transmitting adhesive surface.

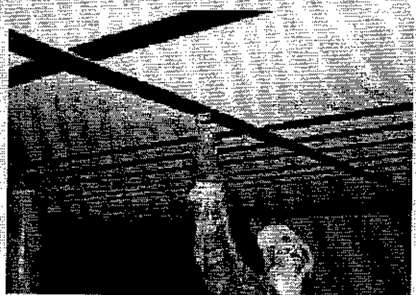
Requirements under Environmental Influences
- ▲ Temperature
- ▲ Moisture
- ▲ Frost
- ▲ Freeze/thaw
- ▲ Corrosion
- ▲ Ultra violet radiation

Corrosion resistance is an important factor in long life. The Sika CarboDur plates have high chemical resistance to the pollutants normally occurring on structures. In particular, there is no risk of underrusting.



Sika® CarboDur® Plates

Advantages
- ▲ Defined performance properties
- ▲ Range of dimensions – optimum design
- ▲ Choice of modulus
- ▲ Factory prepared for use
- ▲ Low temperature application with heated plates
- ▲ Elevated temperature in service grade
- ▲ Can be prestressed
- ▲ Very high strength



Strengthening of the reinforced concrete slab with the Sika® CarboDur® Plate System (Sikadur-30 adhesive and Sika® CarboDur® plates)

SikaWrap® Fabrics

(Glass, Carbon, Hybrid) Wet/Dry Application

Advantages
- ▲ Shear strengthening
- ▲ Impact and blast resistance
- ▲ Very flexible for details
- ▲ Easy on circular and square sections
- ▲ High strength
- ▲ Carbon fiber, glass and hybrid fabrics available

Application of SikaWrap® Fabric System for impact resistance on a bridge column

HEXCEL®

Sika® CarboDur® Composite Strengthening Systems.
A Global Alliance between Sika® and Hexcel®.

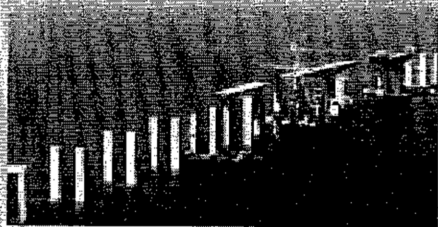
Sika®

Sikadur® – the Long-term Tested, Durable, Epoxy-based Adhesive

Sikadur is a high-quality epoxy adhesive with outstanding physical and chemical properties. Its high mechanical strength and glass transition point prevent creep and guarantee a durable bond between the jointing parts.

In use as a bridge adhesive since 1960.
Tested to FIP standards:
- ▲ Compressive and tensile strength
- ▲ E-modulus
- ▲ Shear strength
- ▲ Pot life
- ▲ Open time
- ▲ Sag flow
- ▲ Groutability
- ▲ Wet adhesion
- ▲ Glass transition point

With predefined detachment at peak cracking stress.




Strengthening with steel plates

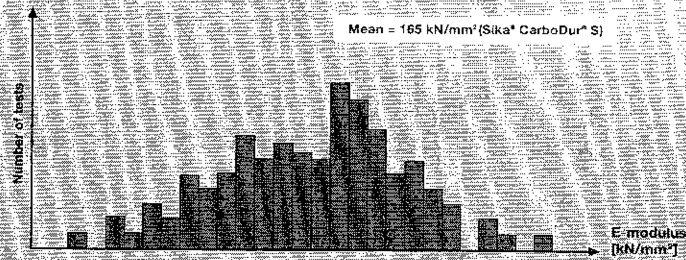
Approval

General construction approval in Germany for steel plate strengthening with Sikadur-30 and Icosit 277	German Institute of Construction 7 - 36.1 - 30	07. 04. 95

Defined Adhesive Performance

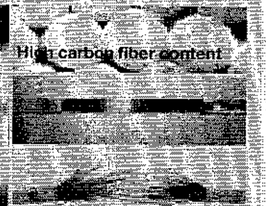
Sika® CarboDur® Plate – the Long-term Tested, Durable CRP Plate

Long experience in the production of Sika CarboDur plates using high-quality carbon fibers. Continuous checks during and after production of the plates.



Quality Checks
- ▲ Tensile strength
- ▲ E-modulus
- ▲ Glass transition point
- ▲ Geometry


Measuring tensile properties


High carbon fiber content

Approval

General construction approval in Germany for Sika CarboDur	German Institute of Construction 7 - 36.12 - 29	11. 11. 97

Defined Plate Performance

Sika® CarboDur® – the Long-term Tested Strengthening System

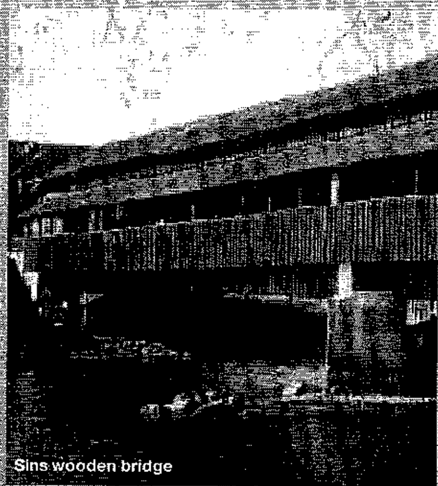
1987 – first trials at EMPA.

Test certificates

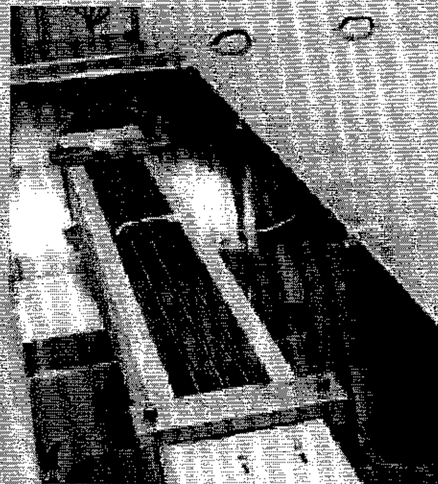
Strengthening of reinforced concrete with carbon fiber reinforced epoxy resins	Thesis ETH Zurich No. 8918	1989
Static and dynamic tests on RC T-beams strengthened with Sika CarboDur	Thesis ETH Zurich No. 10199 (EMPA Report No. 224)	1993

Defined System Performance During Application and in Service

1991 – first uses by EMPA on a reinforced concrete and wooden bridge.


Sins wooden bridge

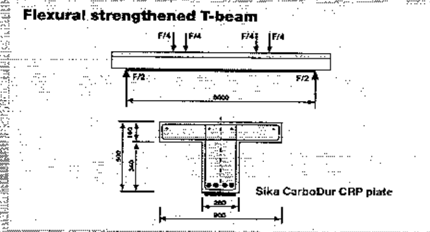
1991 – start of long-term system testing under extreme climatic conditions.

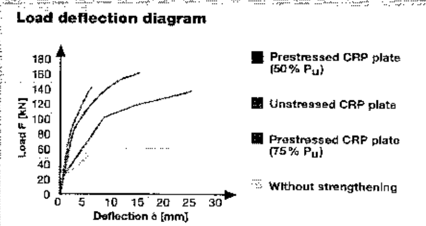


Since 1994 – global market launch. Worldwide support by Sika.

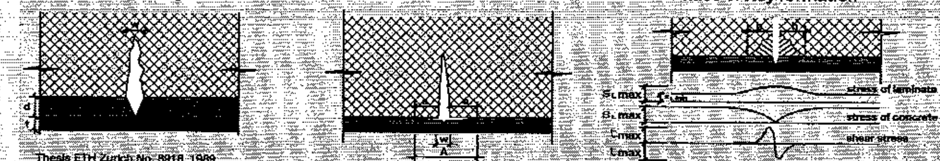
Static Loading on Large T-beams

The Sika CarboDur system has been successfully tested by the EMPA on innumerable reinforced concrete beams.





The mechanism of the crack bridging capacity of the Sika CarboDur strengthening system was also tested on both cracked and uncracked beams. Initially the cracks are bridged by shearing strain in the adhesive. When the crack is enlarged, detachment of the adhesive occurs first, followed by formation of a rupture key.

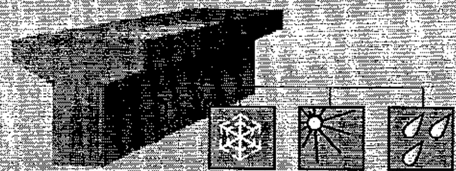


Thesis ETH Zurich No. 8918, 1989

Thermal Cycle Tests on Cracked Concrete Beams

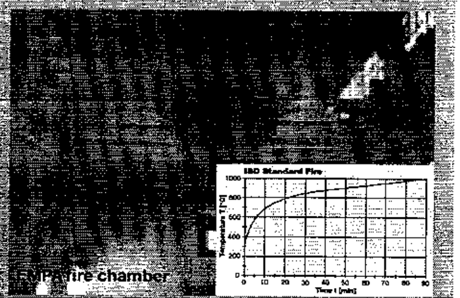
Static and dynamic stress tests were carried out on various reinforced concrete beams strengthened with Sika CarboDur. The beams were subjected to high relative humidity levels and extreme temperatures of -25 °C to +40 °C.

Ice was observed in the cracks during the freeze cycle. Despite this, the subsequent stress tests showed no weakening of the strengthening system.



The Fire Properties of the System

The Sika CarboDur system was tested in the EMPA fire chamber with an ISO standard fire. There was almost no smoke development throughout the period of the test. The plates do not have to be protected from falling because the weight is very small. It was clear that the CarboDur plates can be successfully protected against fire with fire-resistant boards.

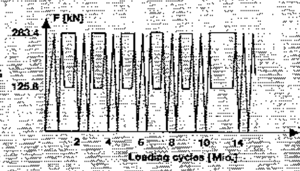


EMPA fire chamber

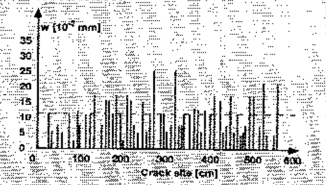
EMPA Test Report No. 148795, 1994

Dynamic Stress on Large T-beams

Reinforced concrete beams strengthened with the Sika CarboDur system were subjected to dynamic stress with high load cycle amplitudes. After a large number of load cycles, the tensile reinforcement bars failed first due to friction corrosion. The behaviour of the Sika CarboDur system was outstanding. The stress amplitude of the internal reinforcement can be reduced by strengthening with the Sika CarboDur system.

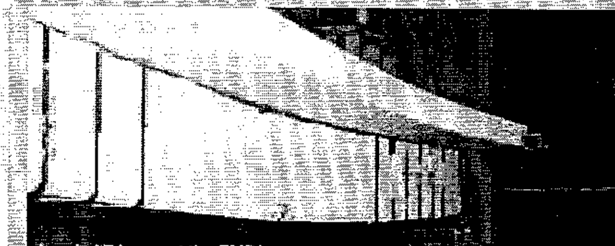


Thesis ETH Zurich No. 10199, 1993



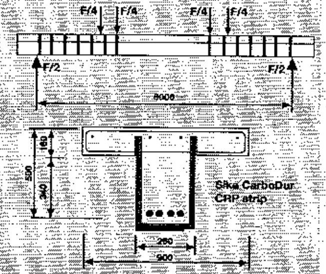
Shear Strengthening

CarboDur stirrups were post-applied in the zones under shear stress instead of the internal reinforcement stirrups. The load-deflection curves showed similar load-bearing properties to those found in the earlier control tests with steel plate strengthening.



Loaded T-beam at the EMPA

EMPA Test Report No. 169219/1+2, 1998 / Patent pending

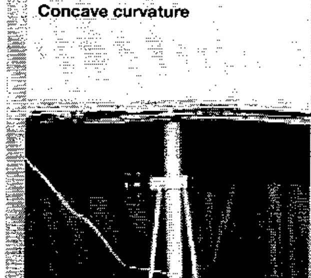


Shear strengthened T-beam

The Sika® Roll-on Process

The maximum design concave curvature of a concrete surface was tested on a reinforced concrete beam.

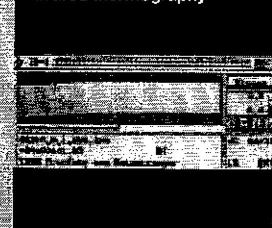
The efficient Sika roll-on process enables the CarboDur plates to be applied in a very short time. This can save considerable working time and also gives greater flexibility in construction planning for strengthening work.



Concave curvature

EMPA Test Report No. 154490/1, 1996

EMPA Test Report No. 154490, 1994

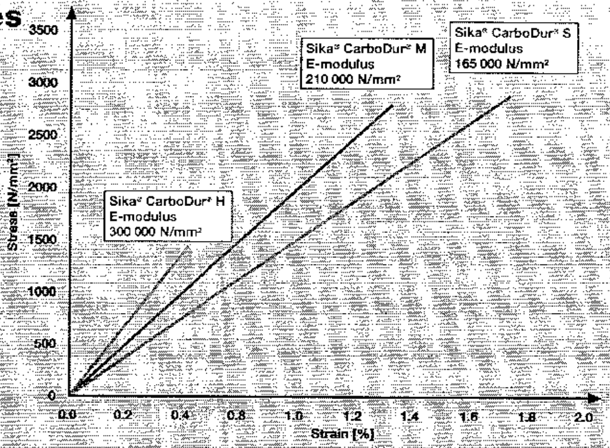


Infrared thermography

Sika test on concrete beam

Different Rigidities

The strengthening of a structure can be optimized by using different CarboDur plate modules. The most suitable plate can be selected according to the type of structure and its loading and span.



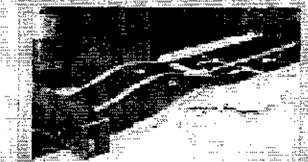
Reinforcement Strain Relief

The reinforcement can have improved strain relief and the crack widths can be reduced by using high-module plates.

Deflection

If strengthening is necessary due to high deflection, for example on timber beams, the Sika CarboDur H plate is used.

Plate under Compressive Stress



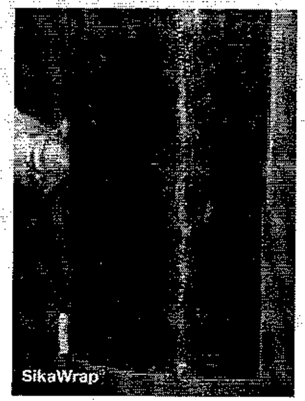
The behaviour of the Sika CarboDur plates in the compression zone is extremely good. Unlike a steel plate, it adheres to the substrate until total destruction of the concrete in the compression zone.

Static and dynamic tests on RC T-beams strengthened with Sika CarboDur	Thesis ETH Zurich No. 10199 (EMPA Report No. 224)	1993

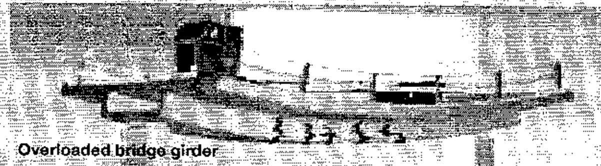
Reinforced Concrete Deck

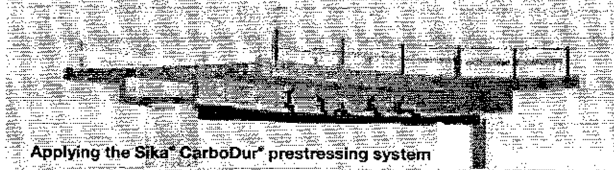
Prestressed Reinforced Concrete Beams

Columns



Post-applied Prestressing


Overloaded bridge girder


Applying the Sika® CarboDur® prestressing system


Prestressed bridge girder

The Sika CarboDur plates can also be prestressed before bonding. This reduces the risk of the plate peeling off due to concrete shear failure in the tension zone, which increases the structural safety. Serviceability can then be further improved compared with a plate bonded without tension. The prestressing force in the plate relieves the strain on the internal steel reinforcement and reduces the deflection and crack widths.

- ▲ Closing the cracks partially
- ▲ Smaller cracks
- ▲ Reinforcement strain relief
- ▲ Increase in serviceability and structural safety

Patent pending

Shortened Anchorage


Patent pending

Specially treated plate end allows reduced anchorage length.

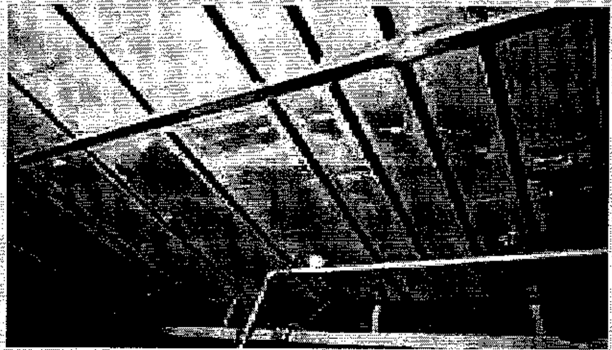
Stone Pillar

Masonry

Timber Beam

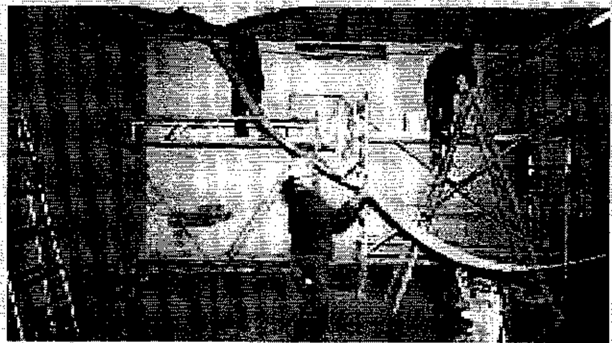
Flexible in Installation

With the flexible Sika CarboDur plates, strengthening work can be carried out without dismantling existing services. This reduces the construction period and also saves money.



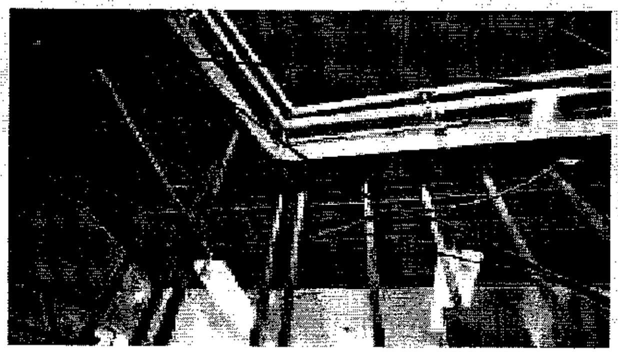
Around Services

- ▲ Water pipes
- ▲ Gas pipes
- ▲ Electric cables
- ▲ Compressed air pipes
- ▲ Ventilation ducts



Through Wall Openings

- ▲ Anchorage lengthening
- ▲ Non-load bearing walls
- ▲ Change in the structural system
- → Long plates
- → Confined spaces



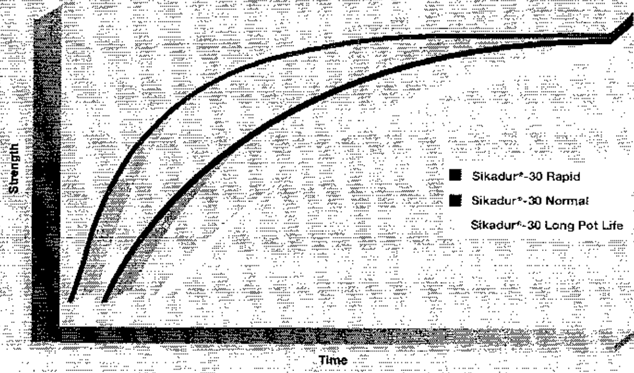
In Lift Shafts and Stairwells

- ▲ Confined spaces
- ▲ Intersected plates

Quick to Use

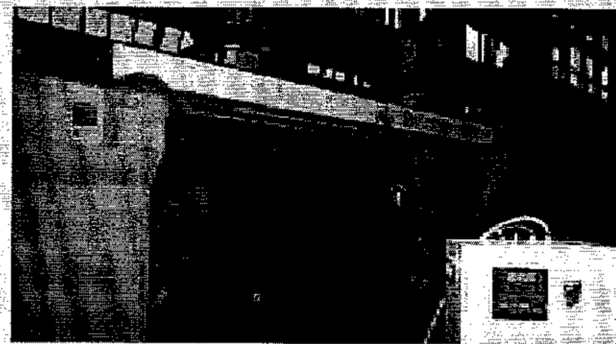
Temperature-based Strength Development

The type of adhesive appropriate for the temperature on the site is used. The installation properties are designed to suit the specific temperature conditions, so that rapid hardening is achieved.



Low Temperatures

Sikadur-30 Rapid type can be used in low temperatures. Its accelerated chemical reaction provides sufficient strength within a short time.



Patent pending

Brief Interruption

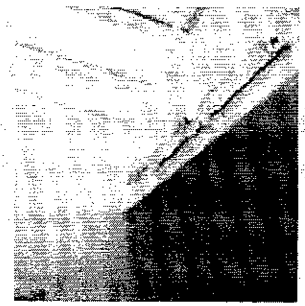
When the Sika CarboDur heating device is used, the Sikadur-30 will harden within hours. The glass transition point is improved at the same time. This allows strengthening work to be carried out with short interruption during the night.

Curing Within Hours

- ▲ High glass transition point (Sikadur-30 Long Pot Life)
- ▲ Night working
- ▲ Strengthening without traffic loads
- ▲ No interruption in fabrication
- ▲ At low temperatures

EMPA Test Report No. 170569, 1998

Appearance

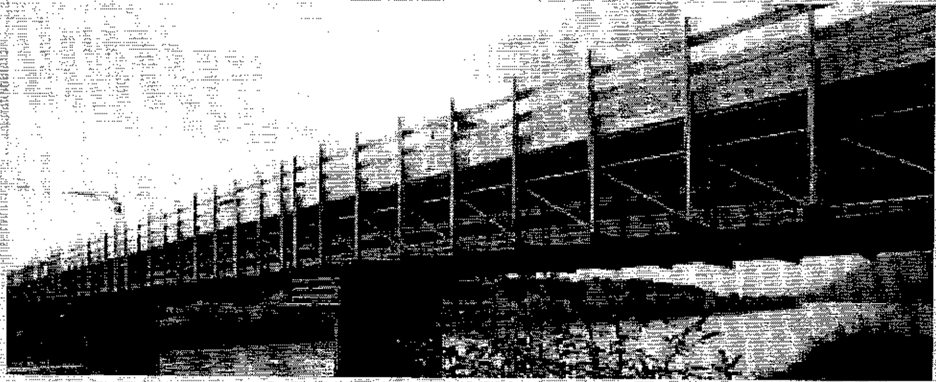


The very thin Sika CarboDur plates can be concealed or integrated within the existing load-bearing structure without expensive operations.

- ▲ Coating the plates
- ▲ Covering with mortar
- ▲ Covering with timber boarding
- ▲ Inserting into a slot

Strengthening of a Bridge Slab due to Increased Traffic Load

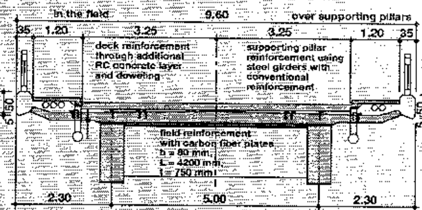
Repairs to the bridge Oberriet-Meiningen over the Rhine (Switzerland/Austria)



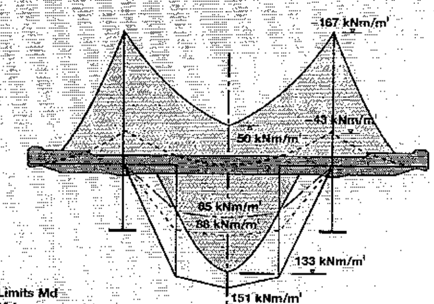
Strengthening the reinforced concrete bridge slab in the transverse direction by:

- ▲ Increasing the concrete compression zone
- ▲ Bending reinforcement with Sika CarboDur S812 at 750 mm centres
- ▲ Total strengthening factor 2.4
  - by the concrete compression zone 1.4
  - by the plates 1.7

Cross-section of composite bridge



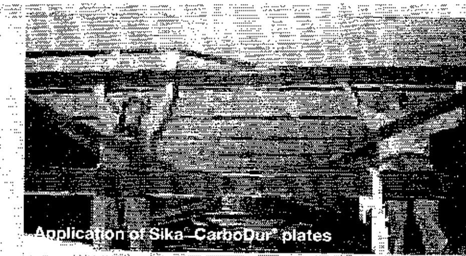
Moment curve



——— Limits Md
- - - - Md permanent

—·—·— M_R/γ_R before strengthening
- - - - M_R/γ_R after adding concrete
——— M_R/γ_R final new cross section

Slab strengthening by concrete overlay.
Bottom reinforcement strengthening with CRP plates.


Application of Sika® CarboDur® plates

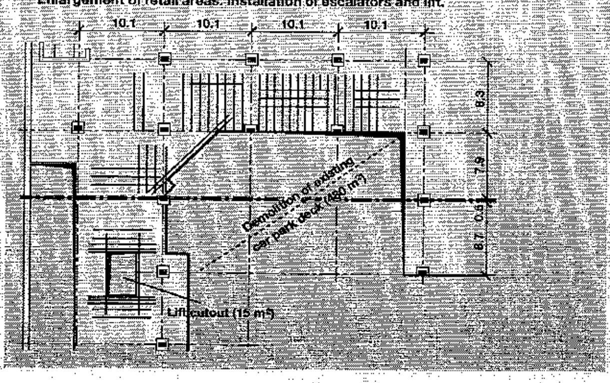

Bridge soffit

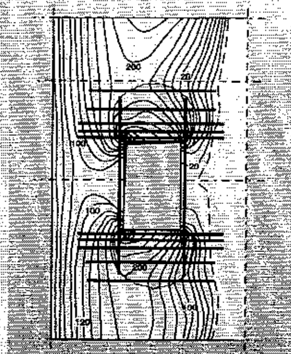

Cross-section through core from pull-off test

Change in the Structural System due to Change of Use

Conversion of a shopping centre in Winterthur (Switzerland). Application of 1.7 km Sika® CarboDur® plates.

Enlargement of retail areas. Installation of escalators and lift.

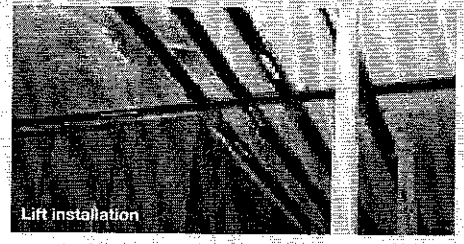




Lift cutout with moment isolines


Escalators installed


Demolition of car park deck after strengthening

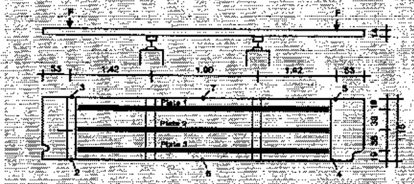

Lift installation

Structural Strengthening due to Inadequate Design

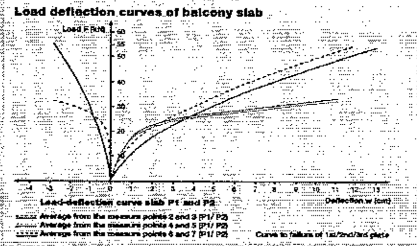
Sagging balcony slabs in Magdeburg (Germany)

Prestressed balcony slabs with insufficient bending reinforcement

→ Sagging balcony slabs with surface water strengthening with 3 Sika CarboDur S512 plates. Advantage: no extra self weight.



Load deflection curves of balcony slab



IBMB Test Report No. 1448/325, 1995

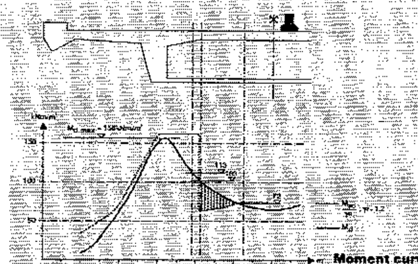

Strengthened balcony slabs


Balcony soffit after coating

Structural Strengthening due to Insufficient Reinforcement

Repairs to the Horgen transporter bridge (Switzerland)

Reinforcement cross section too low on the bridge slab on one side. Missing reinforcement supplemented. System tests at laboratory and on site. Positive results for bitumen membrane torching.

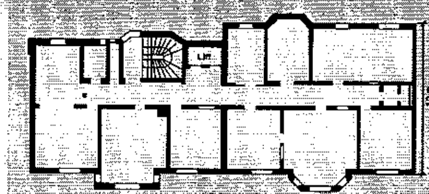



Sika® CarboDur® S1212 plates applied at 600 mm centres

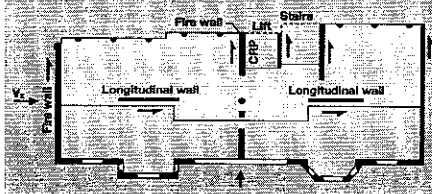

Bitumen membrane torching

Structural Strengthening of Masonry Structures

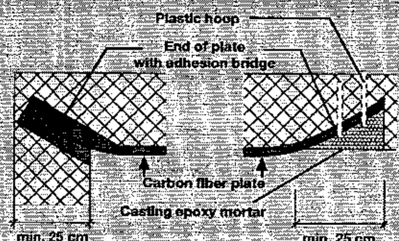
Conversion of a residential building to an office building in Zurich (Switzerland)



Existing load-bearing structure before conversion, 2nd floor



Load-bearing structure after conversion, 1st to 4th floors



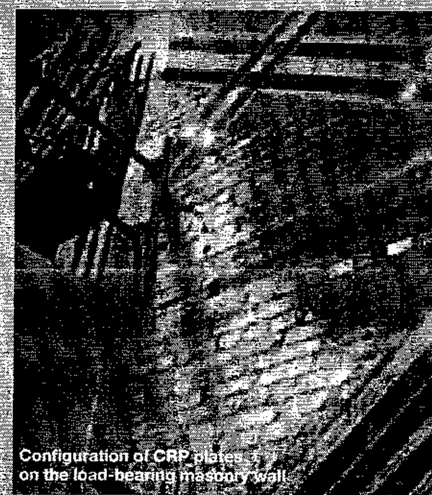
Strengthening of masonry walls on one side for guaranteed earthquake resistance

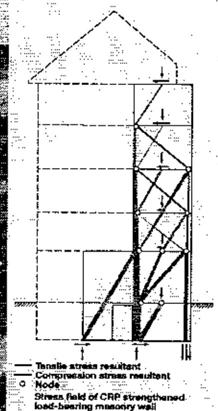
- ▲ Crossbanding of Sika CarboDur S1012 plates
- ▲ Anchorage in the reinforced concrete supports
- → Ductility of the masonry increased
- → Earthquake resistance increased many times over

Strengthening of masonry with heavy duty fiber composite materials	Thesis ETH Zurich No. 10672 (EMPA Report No. 229)	1994


Recess filled with epoxy grout

Plate anchorage in the recess


Configuration of CRP plates on the load-bearing masonry wall

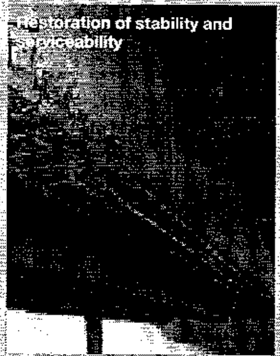


Guarantee of Structural Stability Following Reinforcement Corrosion

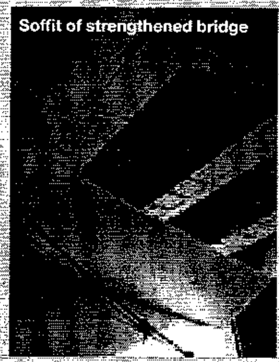
Serious concrete damage and reinforcement corrosion on a reinforced concrete frame bridge in Dresden (Germany)

Replacement of corroded bending steel reinforcement. Reinforcement by three Sika CarboDur S512 plates per beam.

Infill of Sika Injectoflex. Reprofiling with SikaCem-Gunite 133. Carbonation resistance with Sikagard-550.


Restoration of stability and serviceability


Installation of Sika CarboDur S 512 plate


Soffit of strengthened bridge

Strengthening of Existing Roof Beam to take new Floor Loading

Strengthening of ribbed beams at a hospital training centre in London (England)

Ribbed beams eleven metres long 600 mm centres

Doubling of working load by strengthening the beams with Sika CarboDur S512 plates

Pressed into position by roller


Soffit of ribbed beam

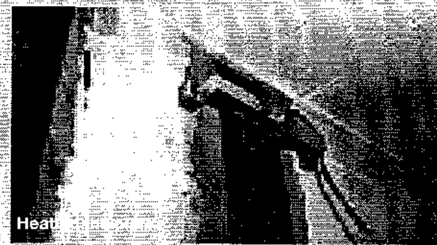

Coating [illegible]


Easy installation of Sika CarboDur plate

Strengthening due to Increased Load and Change of Use

Conversion of a factory into a laboratory and office building in Dübendorf (EMPA, Switzerland)


Strengthening of walls


Heat[illegible]

Change in structural system due to change of use.

Application of the Sika CarboDur during cold temperature with the Sika CarboDur heating device.

Restoration of Original Load-bearing Capacity

Damaged beams in a car park at a shopping mall in Boston (USA)

Strengthening the beams damaged by overloading during construction.


Threading between the services


Pressed into position by roller

Strengthening of Timber Beams due to Insufficient Bearing Capacity

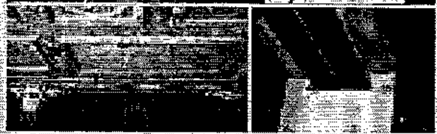
Crack in an oak beam in a museum in Lucerne (Switzerland)

Invisible strengthening of an oak beam

Filling the milled slot with Sikadur

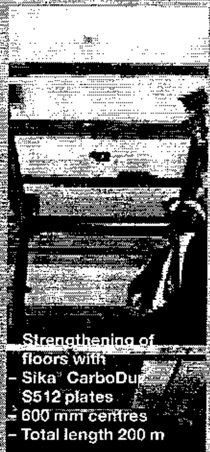
Insufficient structural stability due to conversion in a monastery in Eschenbach (Switzerland)

Strain relief of the beam by two supp
Inserting the Sika® CarboDur® H514 p



Strengthening due to Insufficient Structural Safety

Repair works in a Town Hall in Auckland (New Zealand)



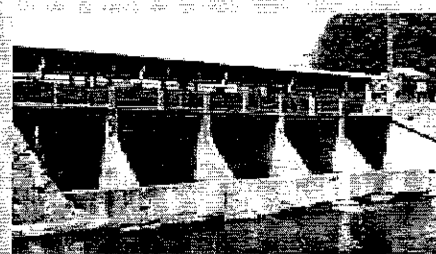
Strengthening of floors with
- Sika® CarboDur S512 plates
- 600 mm centres
- Total length 200 m

Conversion of a residential building into an office building in Budapest (Hungary)

Installing the Sika CarboDur S512 plates

Strengthening of Bridge Deck and Beams due to Increased Service Load

Strengthening of the bridge over Bystry Channel, Augustów (Poland)



Replacement of the carbonated concrete and strengthening of the bridge deck with Sika CarboDur M1214 plates.

Strengthening of the shear zones of the beams with SikaWrap Hex-230C fabrics using Sikadur-330 adhesive.

Strengthening of Bridge Columns for Heavy Vehicle Impact

Strengthening of the Bible-Christian Bridge, A30 Bodmin-by-Pass, Cornwall (UK)

Concrete prepared and primed with Sikadur Hex-300 low viscosity impregnating and sealing epoxy resin.

Sikadur Hex-306 thixotropic epoxy resin adhesive was applied to the glass fibre fabric SikaWrap Hex-100G sheets.

The designed lengths of fabrics were unrolled onto the column and smoothed into position.

aterial Characteristics

² CarboDur® Plates

	Sika®CarboDur® S	Sika®CarboDur® M	Sika®CarboDur® H
iulus	165,000 N/mm²	210,000 N/mm²	300,000 N/mm²
strength	2,800 N/mm²	2,400 N/mm²	1,300 N/mm²
ge measured tensile th	3,050 N/mm²	2,900 N/mm²	1,450 N/mm²
at failure	> 1.7 %	> 1.2 %	> 0.45 %

Wrap® Hex Fabrics

	SikaWrap® Hex-230C	SikaWrap® Hex-103C	SikaWrap® Hex-100G
strength 's	3,500 N/mm²	3,500 N/mm²	2,250 N/mm²
modulus 's	230,000 N/mm²	230,000 N/mm²	70,000 N/mm²

Sikadur® Epoxy Adhesives and Mortars

	Sikadur®-30	Sikadur®-41
Compressive strength	> 95 N/mm²	> 75 N/mm²
Adhesive strength on steel	> 26 N/mm²	> 10 N/mm²
Adhesive strength on concrete	> 4 N/mm² (concrete failure)	> 4 N/mm² (concrete failure)
E-modulus	12,800 N/mm²	9,000 N/mm²

Sikadur® Epoxy Adhesives

	Sikadur®-330	Sikadur® Hex-300/306
Flexural modulus	3,800 N/mm²	3,120 N/mm²
Adhesive strength on concrete	> 4 N/mm² (concrete failure)	> 4 N/mm² (concrete failure)

For additional information see Technical Data Sheets.

st Certificates / Reports

thening of reinforced ıte with carbon fiber ced epoxy resins	Thesis ETH Zurich No. 8918	1989
and dynamic tests on ıeams strengthened ka CarboDur	Thesis ETH Zurich No. 10199 (EMPA Report No. 224)	1993
sts with Sika CarboDur thened RC beams	EMPA Test Report No. 148795	1994
thening of masonry ıavy duty fiber ısite materials	Thesis ETH Zurich No. 10672 (EMPA Report No. 229)	1994
Testing the Sika roll-on process on voids by infrared thermography	EMPA Test Report No. 154490	1994
Static loading tests on concrete beams strengthened with Sika CarboDur	EMPA Test Report No. 154490/1	1995
Loading test on timber stairs strengthened with Sika CarboDur	EMPA Test Report No. 161782	1996
Sika CarboDur shear tests on RC T-beams	EMPA Test Report No. 169219/1+2	1998
Application of Sika CarboDur on vibrating RC slabs	EMPA Test Report No. 170569	1998

chnical Articles

adhesives for permabond jointing. H. Bänziger, W. Steiner, 1989.
thening of reinforced concrete with tensioned fiber composites.
ring, 1993.
ates in construction. Strengthening of concrete structures.
ıring, 1994.
thening of structures with fiber composites. U. Meier, 1994.
thening with CRP plates. M. Deuring, W. Steiner, 1996.
:hening of the Oberriet-Meiningen Rhine bridge. R. Walser, W. Steiner, 1996.
ıake resistance of masonry structures strengthened with fibre composites.
wegler, P. Kelterborn, 1996.

Approvals

General construction approval in Germany for steel plate strengthening with Sikadur-30 and Icosit 277	German Institute of Construction 7-36.1-30	07.04.95
General construction approval in Germany for Sika CarboDur	German Institute of Construction 7-36.12-29	11.11.97

Your Local Sika® Company